

The kangaroo's first hop: the early fast cooling phase of EP250108a/SN 2025kg

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ABSTRACT

Fast X-ray transients (FXTs) are a rare and poorly understood population of events. Previously difficult to detect in real time, the launch of the *Einstein Probe* with its wide field X-ray telescope has led to a rapid expansion in the sample and allowed the exploration of these transients across the electromagnetic spectrum. EP250108a is a recently detected example linked to an optical counterpart, SN 2025kg, or ‘the kangaroo’. Together with a companion paper (Rastinejad et al. 2025), we present our observing campaign and analysis of this event. In this letter, we focus on the early evolution of the optical counterpart over the first six days, including our measurement of the redshift of $z = 0.17641$. We compare to other supernovae and fast transients showing similar features, finding significant similarities with SN 2006aj and SN 2020bvc, and show that the source is well-modelled by a rapidly expanding cooling blackbody. We show the observed X-ray and radio properties are consistent with a collapsar-powered jet that is low energy ($\lesssim 10^{51}$ erg) and/or fails to break out of the dense material surrounding it. While we examine the possibility that the optical emission emerges from the shock produced as the supernova ejecta expand into a dense shell of circumstellar material, due to our X-ray and radio inferences, we favour a model where it arises from a shocked cocoon resulting from the trapped jet. This makes SN 2025kg one of the few examples of this currently observationally rare event.

Keywords: X-ray transient sources (1852) — High energy astrophysics (739) — Type Ic supernovae (1730) — Gamma-ray bursts (629)

1. INTRODUCTION

The *Einstein Probe* (hereafter *EP*, Yuan et al. 2022), launched just over a year ago, and has already made significant contributions to the field of high energy X-ray astronomy. In particular, it has vastly increased the known sample of fast X-ray transients (FXTs) with its Wide-field X-ray Telescope (*EP*/WXT).

FXTs are outbursts detected in the soft X-ray regime (typically < 10 keV), and are characterised by timescales of tens to thousands of seconds. While they were found in early sounding rocket experiments, until recently, the meaningful samples have been identified in targeted searches of archival data (e.g. Jonker et al. 2013; Glenne et al. 2015; Bauer et al. 2017; Alp & Larsson 2020; De Luca et al. 2021; Quirola-Vásquez et al. 2022, 2023). While there are exceptions to this rule, such as the fortuitous detection of the X-ray flare that accompanied the type Ib supernova SN 2008D (e.g. Mazzali et al.

2008; Soderberg et al. 2008; Modjaz et al. 2009; Malesani et al. 2009), these have historically been extremely rare. However, in only a year of operations, *EP*/WXT has detected \sim one hundred FXTs and vastly increased the observed sample of these rare transients. These FXTs have been detected and communicated to the community in near real time and allowed in depth analysis of many of their counterparts across the electromagnetic spectrum.

The properties of the FXTs detected by *EP* are diverse and likely represent a wide range of transient types and progenitor systems. While the nature and origins of many remain mysterious (e.g. Zhang et al. 2025; O’Connor et al. 2025), several have been linked to the core collapse of massive stars. Both EP240219a and EP240315a, for instance, were linked to collapsar-driven long gamma-ray bursts (GRBs; e.g. Yin et al. 2024; Levan et al. 2024; Liu et al. 2025b). In these particular

cases, the FXT is likely the lower energy counterpart of internal shocks in a powerful relativistic jet produced by the cataclysmic collapse of these stars. Other *EP* FXTs have also been seen to be linked to Type Ic supernovae (van Dalen et al. 2025; Sun et al. 2024; Srivastav et al. 2025) which are known to be produced by similar progenitors as long GRBs and are often observed following such an event (e.g. Woosley et al. 1999; Woosley & Bloom 2006; Georgy et al. 2009; Modjaz et al. 2016).

However, the sources linked to FXTs have often proven to be unusual when compared to the respective populations of these events as observed by other facilities. For example, EP240315a was shown to exhibit soft X-ray emission hundreds of seconds earlier and for far longer than the gamma-ray emission (Liu et al. 2025b), suggesting significant central engine activity outside the window suggested by the gamma-rays. As another example, SN 2024gsa, the type Ic supernova linked to EP240414a, was accompanied by two distinct thermal emission episodes between the FXT detection and the rise of the supernova suggesting a link to fast blue optical transients (FBOTs; Sun et al. 2024; van Dalen et al. 2025; Srivastav et al. 2025).

FBOTs are fast evolving and bright at ultraviolet and optical wavelengths. Similarly to the term FXT, FBOT indicates a phenomenological rather than physical description and the observed population is therefore diverse. Several subclasses, such as luminous FBOTs (LFBOTs, e.g. Perley et al. 2019; Coppejans et al. 2020; Perley et al. 2021; Bright et al. 2022; Ho et al. 2022c; Gutiérrez et al. 2024a), have been identified and the differing natures of these classes implies FBOTs arise from a variety of systems and progenitors. EP240414a/SN 2024gsa implies the existence of systems where weak jets fail to efficiently break out of a dense stellar envelope or circumstellar medium (CSM). Rather than producing a long GRB, the resulting shocked material produces a blue thermal component providing an origin for some FBOTs.

In this letter, we present our observations and analysis of the early evolution of a unique FXT, EP250108a, detected by *EP*/WXT on 8 January 2025 (Li et al. 2025a) and which allows us to probe the origin of these enigmatic transients. While this event was reported some 18 hours after the detection and further X-ray observations identified no continued emission (Li et al. 2025b), our rapid optical follow-up identified a counterpart (Eyles-Ferris 2025) and prompting multiwavelength observations by the community. EP250108a’s optical counterpart was quickly found to be unusual with a spectral energy distribution (SED) consistent with a hot thermal source (Zhu et al. 2025a; Malesani et al. 2025; Zhu

et al. 2025b) characteristic of a fast blue optical transient, tidal disruption event or supernova rather than a power law as is typical for a GRB afterglow. This behaviour is similar to that exhibited by SN 2024gsa, the first *EP* FXT SN, or that of (L)FBOTs. Based on its initial moniker of AT 2025kg, EP250108a’s optical counterpart was dubbed ‘the kangaroo’. The thermal source rapidly faded before starting to rebrighten ~ 7 days post detection (Song et al. 2025; Eyles-Ferris et al. 2025). Spectroscopic observations showed the rebrightening to be a rising type Ic broad lined (Ic-BL) supernova (Xu et al. 2025; Levan et al. 2025b) and the optical source became SN 2025kg, which we explore in further detail in Rastinejad et al. (2025). Notably, at its redshift of $z = 0.17641$ (see below), SN 2025kg is the currently the closest *EP* FXT with a SN connection.

Here we present the early evolution of EP250108a/SN 2025kg covering the first six days (observer frame) post *EP*/WXT detection, hereafter referred to as the fast cooling phase. We also include X-ray and radio data covering the first 20 and 43 days respectively, which we use to inform our analysis of the presence of a jet. The later UV/optical/IR evolution of the source, particularly the Ic-BL supernova, is explored in a companion paper (Rastinejad et al. 2025).

EP250108a/SN 2025kg is a valuable opportunity that has been seized by several groups in the community, in particular Srinivasaragavan et al. (2025) and Li et al. (2025d). We also compare our results to these papers where appropriate.

Throughout this Letter, we adopt a Planck cosmology (Planck Collaboration et al. 2020). At SN 2025kg’s redshift of $z = 0.17641$, this corresponds to a distance of 880.6 Mpc. Throughout this work, errors are given to $1\text{-}\sigma$.

2. OBSERVATIONS AND DATA REDUCTION

Our observing campaign for SN 2025kg has been extensive in terms of both time and wavelength coverage. In this Section, we summarise the observations taken during the fast cooling phase and their reduction.

2.1. Ultraviolet, optical and NIR

2.1.1. Photometry

During the fast cooling phase, we obtained photometric observations with seven telescopes with a total exposure time in excess of 20 ks. We present our assembled photometry for the fast cooling phase of SN 2025kg in Table 3, also including the photometry reported in GCN Circulars, and show the complete light curve in Figure 1. In our analysis, we correct our photometry for a Milky Way extinction of $A_V = 0.049$ (Schlafly & Finkbeiner

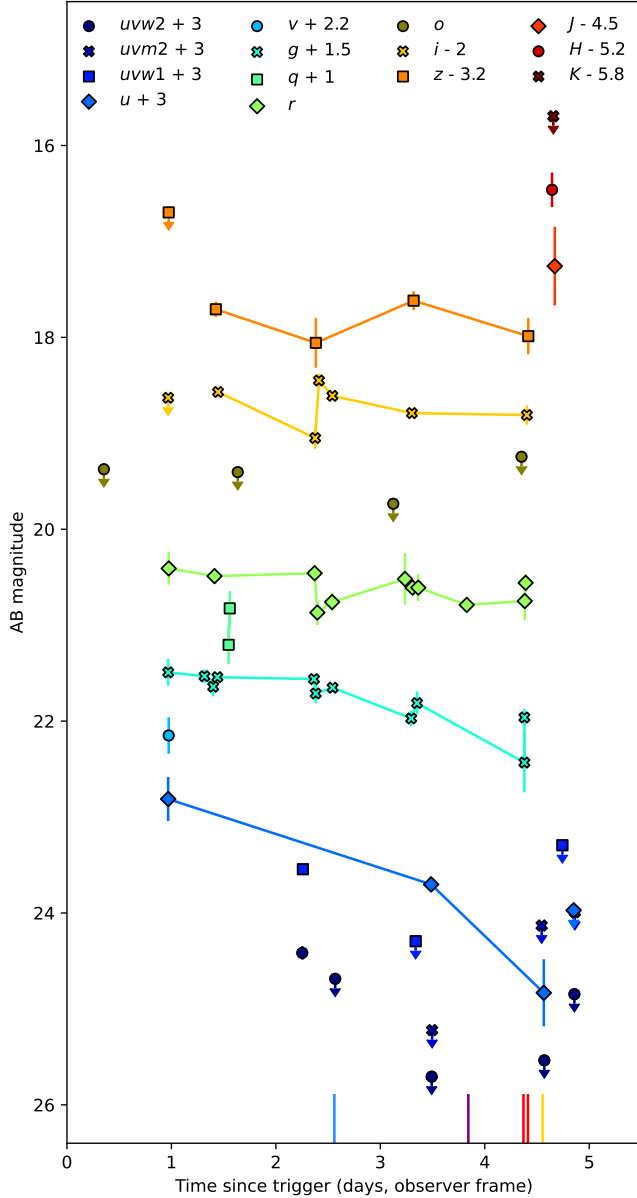


Figure 1. The UVOIR light curve of SN 2025kg’s fast cooling phase. The photometry has been corrected for Galactic extinction of $A_V = 0.049$ (Schlafly & Finkbeiner 2011) using the Gordon et al. (2023) Milky Way model. The vertical lines indicate the times of our spectroscopic observations (with colours corresponding to Figure 4).

2011) using the `dust_extinction v1.5` package (Gordon 2024) and the Gordon et al. (2023, see also Gordon et al. (2009); Fitzpatrick et al. (2019); Gordon et al. (2021); Decleir et al. (2022)) Milky Way model with $R_V = 3.1$.

Following the detection of EP250108a, observations were initiated with the 2m Liverpool Telescope (LT, Steele et al. 2004) using the IO:O instrument (Pro-

gram IDs PL24B06 & PL25A25, PI Eyles-Ferris). Six 200 s frames covering the full error region were obtained in the g filter ~ 31.5 hours after the X-ray trigger. These were promptly processed by the automatic pipeline and then by a modified version of the `photometry-sans-frustration` (`psf`) package¹ (Nicholl et al. 2023). The individual frames were aligned, stacked and a template image from the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS or PS1) subtracted using the ZOGY algorithm (Zackay et al. 2016) as implemented by the PyZOGY package (Guevel et al. 2021). A bright source was identified in the subtracted image and its flux measured from the stacked image using PSF photometry calibrated to nearby PanSTARRS stars. This source, later designated SN 2025kg, or the kangaroo, was promptly announced (Eyles-Ferris 2025). We show the discovery image in Figure 2. Additional optical photometry was obtained using LT/IO:O for two further nights during the fast cooling phase, covering the g , r , i and z filters. These data were reduced using the same procedure as above.

We further obtained extensive photometric observations from the Nordic Optical Telescope (NOT) using the Alhambra Faint Object Spectrograph and Camera (ALFOSC) instrument (in *griz*; Program ID 70-301, PI Jonker), the Sinistro imager on the Las Cumbres Observatory’s (LCO) South African Astronomical Observatory node 1m telescope (*gr*; Program ID SUPA2024B-004, PI Izzo), BlackGEM (q , Groot et al. (2024); Local Transient Survey program) and Gemini-South’s FLAMINGOS2 (JH ; Program ID GS-2024B-Q-105, PI Rastinejad). These data were processed using their respective observatory’s pipelines and the flux of SN 2025kg measured using standard methods. Acquisition images from our spectroscopic observations using the Very Large Telescope’s (VLT) X-shooter and Gemini-North’s GMOS-N were also analysed to supplement our photometry.

To better characterise the properties of the source, particularly at higher energies than accessible through ground based telescopes, we requested three ToO observations by the *Neil Gehrels Swift Observatory* (hereafter *Swift*). These were performed by *Swift* between January 10 and January 13 2025. We acquired the resulting data from the UK *Swift* Science Data Centre² (UKSSDC) specifically that obtained by the X-ray Telescope (XRT) and Ultraviolet/Optical Telescope (UVOT). Given the

¹ <https://github.com/mnicholl/photometry-sans-frustration>

² <https://www.swift.ac.uk/index.php>

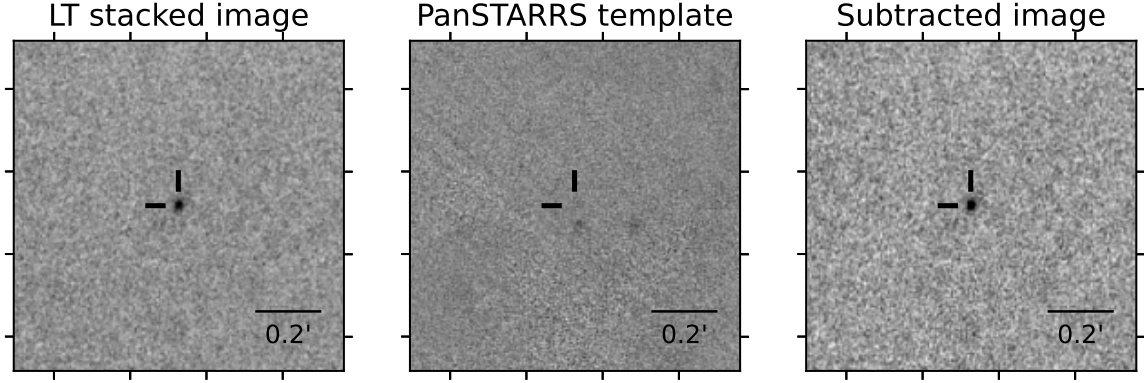


Figure 2. The discovery image of SN 2025kg. The stacked g LT IO:O band image is shown on the left, the PanSTARRS template is shown in the centre and the subtraction is shown on the right. The images are oriented with North to the top and East to the left and the position of SN 2025kg is marked with the cross hairs.

blue nature of the transient, we requested observations in the u , $w1$, $m2$ and $w2$ filters covering wavelengths from 3465 Å down to 1928 Å. We used UVOTPROD-UCT v2.9³ to measure SN 2025kg’s flux using a circular aperture with a radius of 5'' and a 3- σ detection threshold and converted to AB magnitudes using the standard UVOT zeropoints (Breeveld et al. 2011).

To complete our photometry, we used the forced photometry services of the Asteroid Terrestrial-impact Last Alert System⁴ (ATLAS, Tonry et al. 2018; Smith et al. 2020; Shingles et al. 2021) and the Zwicky Transient Facility (ZTF, Masci et al. 2019, 2023) to measure the flux at SN 2025kg’s position from a few days prior to its detection. For both observatories, we processed the forced photometry into single night epochs following the procedure detailed in the ZTF forced photometry documentation⁵ with slight modifications for the ATLAS data. We set a 5- σ detection threshold and calculate 3- σ upper limits. In both cases, only upper limits were derived and we report these in Table 3. Nevertheless, these upper limits are constraining, particularly a deep upper limit from ZTF ~ 2.3 days prior to the trigger and an ATLAS upper limit only ~ 0.4 days (observer frame) post trigger.

We examine the evolution of the SED of the fast cooling phase by dividing the light curve into epochs and fitting them independently with a blackbody. We limit each epoch to covering up to 0.06 days (observer frame) and derive parameter distributions using Monte Carlo analysis, varying the data within errors and refitting

Table 1. The blackbody properties inferred from fits to the SED derived from various epochs of our photometry. Δt is given in the observer frame.

Δt (days)	T_{bb} (10^4 K)	R_{bb} (10^{15} cm)	$\log \left(\frac{L_{\text{bb,bol}}}{\text{erg s}^{-1}} \right)$
0.97150	$2.05^{+1.05}_{-0.55}$	$0.79^{+0.35}_{-0.25}$	$43.90^{+0.59}_{-0.22}$
1.42495	$1.91^{+0.30}_{-0.22}$	0.83 ± 0.10	43.83 ± 0.14
2.38689	$2.15^{+0.72}_{-0.48}$	0.70 ± 0.17	43.88 ± 0.28
2.54063	$2.21^{+0.58}_{-0.34}$	0.69 ± 0.13	$43.91^{+0.22}_{-0.15}$
3.30612	$1.22^{+0.14}_{-0.10}$	1.23 ± 0.15	43.40 ± 0.07
4.37953	$1.57^{+0.32}_{-0.24}$	0.91 ± 0.17	43.55 ± 0.14

100 times. We plot the resulting SEDs in Figure 3 and present the inferred temperatures, radii and luminosities in Table 1. We note that we have assumed the SED to be sufficiently accurately represented by a single backbody. However, due to varying optical depth, ejecta temperatures and other factors, the true SED is more likely a superposition of thermal and/or non-thermal emission. While we acknowledge these caveats (and in our advanced modelling below use a more complete description of the SED), this model provides a strong fit to the data and is useful for inferring the bulk properties of the transient and its evolution, guiding further analysis.

2.1.2. Spectroscopy

During the fast cooling phase of SN 2025kg, we obtained four spectra from the VLT, Gemini-North and the Gran Telescopio Canarias (GTC). We summarise these observations and our data reduction here. Table 4 presents a log of our spectroscopic observations and we show the full spectral sequence in Figure 4.

³ As part of HEASOFT v6.32 (Nasa High Energy Astrophysics Science Archive Research Center (Heasarc) 2014).

⁴ <https://fallingstar-data.com/forcedphot/>

⁵ https://irsa.ipac.caltech.edu/data/ZTF/docs/ztf_forced_photometry.pdf

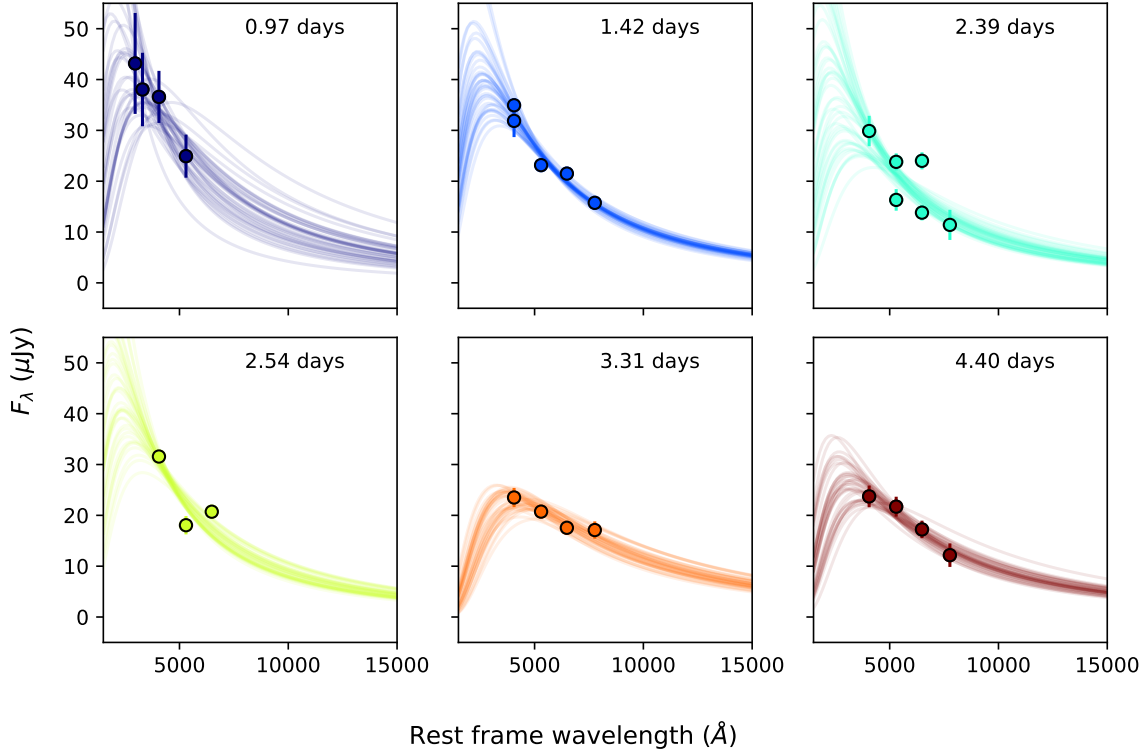


Figure 3. The photometric SEDs of SN 2025kg at various epochs (given in the observer frame) fitted with sampled blackbody models.

Both VLT spectra were obtained with the X-shooter instrument (Vernet et al. 2011), a multi-wavelength, medium-resolution spectrograph installed at the European Southern Observatory (ESO) VLT UT3/Melipal (Program ID 114.27PZ.001, PI Tanvir). X-shooter covers a total range of $\sim 3000 - 25000$ Å with a slit width of 0.9 or 1.0'' depending on the arm. Our VLT spectra were reduced using the standard ESO REFLEX pipeline (Freudling et al. 2013). Here, due to SN 2025kg’s blue nature and low redshift, we utilise only the data from the UVB and VIS arms covering $\sim 3000 - 10000$ Å, specifically the 1D spectra reduced in STARE mode. The arms were normalised to each other using their common wavelength area and each spectrum is flux calibrated using the closest photometry in time.

The Gemini-North spectrum was obtained with the GMOS-N instrument (Program ID GN2024B-Q-107, PI Rastinejad) with a slit width of 1''. The data were reduced using the PyPeIt (Prochaska et al. 2020) package and again flux calibrated using photometry closest in time.

Finally, the OSIRIS+ instrument was used to obtain the spectrum observed by GTC (Program ID GTC1-24ITP, PI Jonker). Data were obtained using both the R1000B and the R1000R grating. A 1'' slit width was used for each of the two grating observations and the

seeing as measured from the width of the spectroscopic trace is $1.2 \pm 0.1''$. We correct for bias, flats, calibrate in wavelength using arc lamps, and optimally extract the spectra using pyraf and MOLLY tasks. Sub-pixel drifts on the position of the [O I] $\lambda 6300$ Å sky emission line were employed to correct for flexure effects on the wavelength calibration. The spectra were also corrected from the Earth movement using MOLLY tasks. Flux calibration was performed using observations of the flux standard G191-B2B at the end of the night. We corrected for slit losses, considering wavelength dependent seeing as well as airmass correction. However, we note that the non-simultaneous observation of the target and the standard introduces uncertainties to the flux calibration due to atmospheric variability.

To further constrain the properties of SN 2025kg, we fit our spectral continua with the same blackbody model previously applied to the photometric epochs. We use a signal to noise ratio (SNR) cut of $\text{SNR} > 3$ per bin, fit only to those data and correct for Milky Way extinction using the same model and $A_V = 0.049$ mag as our photometric analysis. In the case of the second X-shooter spectrum, due to the increasing opacity from elements formed by nucleosynthesis in the rising supernova, the spectrum is not purely thermal, particularly at blue wavelengths. We therefore apply an additional

cut and fit only the data with an observed wavelength $> 5500 \text{ \AA}$ (4700 \AA in the rest frame) with the blackbody. Blackbody spectra with parameters set to the median values (i.e., the values reported in Table 4) are plotted in black over the spectrum for each epoch in Figure 4 and the inferred properties included in Table 4. Our results show that, consistent with the photometry, the spectral sequence is broadly consistent with a cooling, expanding blackbody.

2.1.3. Redshift

Our spectroscopic observations reveal clear evidence for emission lines from the underlying host galaxy, including lines from [OII], [OIII], $H\beta$ and $H\alpha$ (see Figure 4). Measured from our first epoch X-shooter spectrum, these lines provide a systematic redshift for the host galaxy of $z = 0.17641 \pm 0.0003$. In addition we also observe absorption lines in the blue arm from Ca H& K at a similar consistent redshift of $z = 0.17637 \pm 0.0002$. In our cosmology, the luminosity distance is therefore 880.6 Mpc.

2.2. X-ray

EP250108a was originally discovered in X-rays and we also performed additional observations to constrain its behaviour at these energies. We summarise our observations and results in Table 5 and show the X-ray light curve of EP250108a in Figure 5, including the initial detection (Li et al. 2025a,c) and upper limit reported by Li et al. (2025b).

We observed the field of EP250108a using XMM-Newton starting at 17:24:49 (UTC) on 14 January 2025 (Program ID 096168, PI Jonker). The data were processed with SAS version 20230412_1735. After filtering for background flares the effective exposure for the pn detector is 30.44 ks, while it is 48 and 47.4 ks for the MOS1 and MOS2 detectors, respectively. However, for the MOS1 and MOS2 detectors we could only choose a source-free background region on an adjacent detector as the use of the Prime Partial Window of the central detector limited the field of view covered by that detector, leaving no room to estimate the background effectively. Given the larger uncertainties associated with estimating the background on another detector, and because of the higher pn sensitivity, we only consider the pn detector measurements for our upper limit calculations. From visual inspection of the image made from the filtered pn data we conclude we do not detect a source at the position of the optical transient. We calculated the number of source counts needed to be detected in a circle of $10''$ radius in order to be $3\text{-}\sigma$ above the expected background in such a region in the energy range 0.5-10 keV. We used this number of 64 counts to calculate a 95% confidence

upper limit on the 0.5-10 keV unabsorbed source flux of $\lesssim 1 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ assuming a power law spectrum with index 3.03 as observed by Li et al. (2025c).

We obtained further observations with the Chandra X-ray Observatory (DDT Program ID 30747, PI Jonker). An observation was obtained starting at 20:35:15 (UTC) on 28 January 2025 for 10.851 ks. The source was placed at the default location on the ACIS-S3 chip which was operated in the VERY FAINT mode.

The Chandra data were processed using CIAO v4.16. We detect no photons in a circle of $1''$ radius centred on the source localisation. Using the method of Kraft et al. (1991) we obtain a 90% confidence upper limit of 2.3 counts. Again assuming the spectrum observed by Li et al. (2025c), this corresponds to a 0.5-10 keV unabsorbed source flux upper limit of $5 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$.

We also investigate the X-ray data acquired by Swift in our ToO observations, plus two additional observations also undertaken by Swift. No source was identified in any single observation. The Living Swift-XRT Point Source Catalogue Upper Limit Server⁶ (Evans et al. 2023) automatically derives $3\text{-}\sigma$ upper limits which range from 0.002 to 0.009 count s^{-1} . Using PIMMS v4.15 and the spectrum reported in Li et al. (2025c), this indicates unabsorbed 0.5 - 10 keV flux upper limits of 3.1×10^{-14} to $1.2 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. Along with the XMM-Newton and Chandra data, we convert these to luminosities and include them in Table 5.

2.3. Radio

We observed the position of EP250108a with the MeerKAT radio telescope (Camilo et al. 2018; Jonas 2018), as part of program SCI-20241101-FC-01 (PI Carotenuto) and summarise our observations in Table 6. We conducted **four** observations log-spaced in time, each with the same total on-source time of 42 minutes. The first observation started on 13 January 2025 at 17:57 UTC (5.2 days after the first X-ray detection). The second and third observations were performed on 30 January 2025 at 13:41 UTC (22.0 days after the first X-ray detection) and 20 February 2025 at 15:55 UTC (43.2 days after the first X-ray detection), respectively. **A fourth observation was performed on 3 April 2025 at 09:24 UTC (84.9 days after the first X-ray detection).**

We observed at a central frequency of 3.06 GHz (S-band, S4), with a total bandwidth of 875 MHz. PKS J1939-6342 and PKS J0409-1757 were used as flux

⁶ <https://www.swift.ac.uk/LSXPS/ulserv.php>

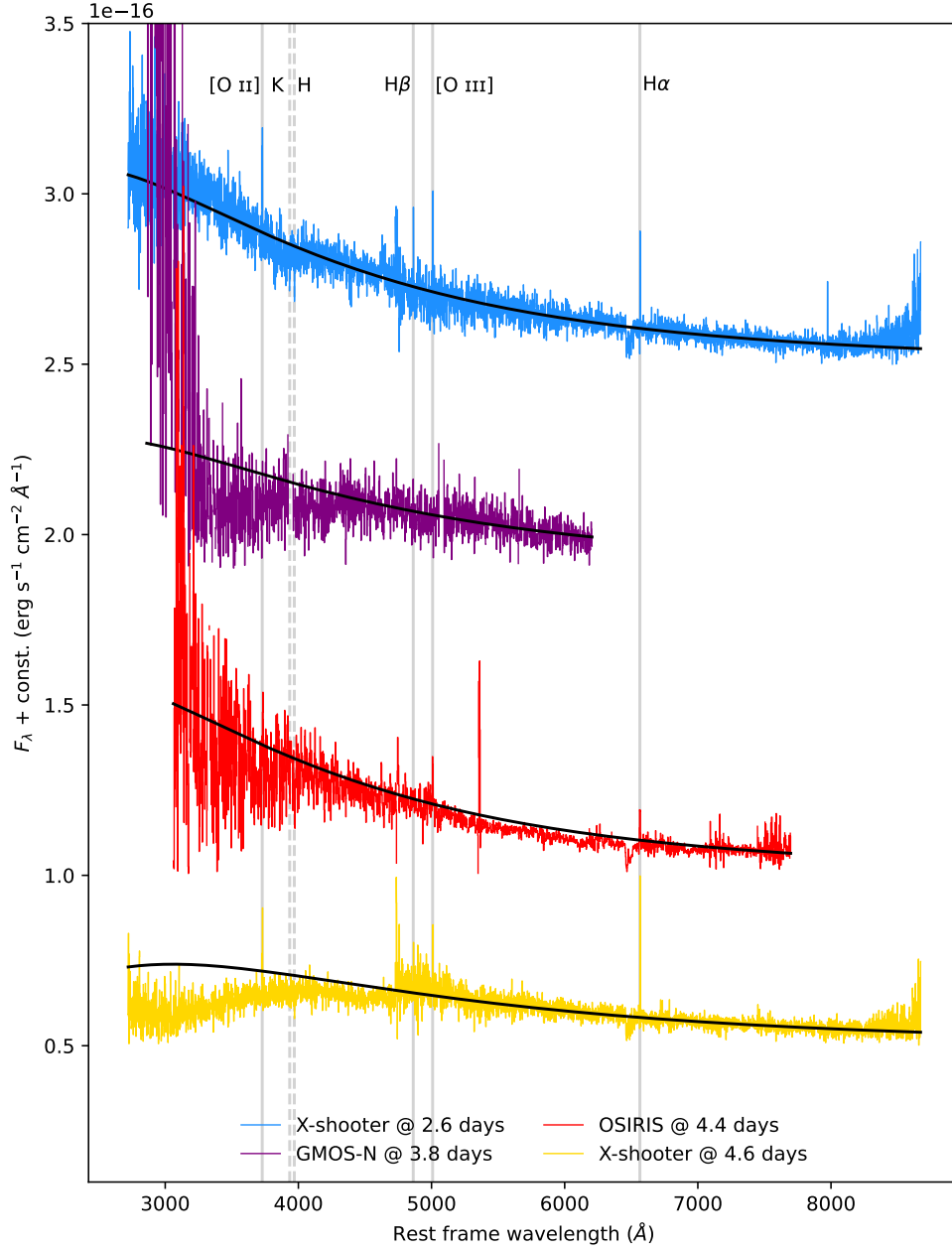


Figure 4. The spectral sequence of SN 2025kg’s fast cooling phase with times given in the observer frame. Emission and absorption lines typically detected in galaxy spectra are marked in solid and dashed grey lines, respectively. In addition, blackbody fits to each continuum (see text) are plotted in black.

and complex gain calibrators, respectively. The data were reduced with the *0xKAT* pipeline (Heywood 2020), which performs standard flagging, calibration and imaging using *tricolour* (Hugo et al. 2022), *CASA* (CASA Team et al. 2022) and *WSCLEAN* (Offringa et al. 2014), respectively. In the imaging step, we adopted a Briggs weighting scheme with a -0.3 robust parameter, yielding a $2.8'' \times 2.8''$ beam and a $8 \mu\text{Jy beam}^{-1}$ rms noise in the target field.

We do not detect radio emission at the position of the optical counterpart of EP250108a, and we place a 3σ upper limit on the flux density of the target at 24, 24, 27, and **26** $\mu\text{Jy beam}^{-1}$ for the first, second, third, and fourth observation, respectively.

3. SN 2025KG AND OTHER TRANSIENTS WITH EARLY THERMAL FEATURES

EP’s unprecedented observational capabilities are likely to uncover a significant population of events

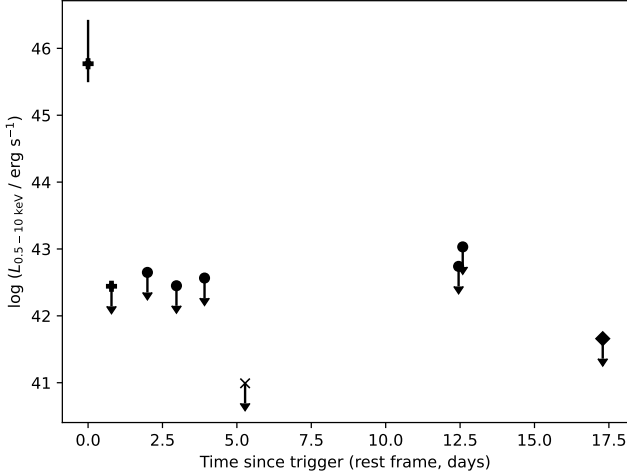


Figure 5. The X-ray light curve of EP250108a including data available in GCNs from *EP* (Li et al. 2025b,c, pluses) and from our observations with *XMM-Newton* (cross), *Chandra* (diamond) and *Swift* (circles). Note the *EP* detection is the luminosity from 0.5 to 4 keV as given in Li et al. (2025c).

similar to EP250108a/SN 2025kg in the near future. For instance, a source with similar optical properties, EP250304a (Chen et al. 2025; Liu et al. 2025a; Page et al. 2025; Saccardi et al. 2025; Shilling & Swift UVOT Team 2025), was detected during the preparation of this Letter. However, there are also a number of previously detected core-collapse supernovae with similar cooling phases. Here we compare the observed properties of SN 2025kg to a selection of these supernovae including SN 2006aj (Campana et al. 2006; Mirabal et al. 2006; Soller et al. 2006; Ferrero et al. 2006), SN 2008D (Mazzali et al. 2008; Soderberg et al. 2008; Modjaz et al. 2009; Malesani et al. 2009), SN 2010bh (Cano et al. 2011; Olivares E. et al. 2012; Bufano et al. 2012), SN 2017iuk (D’Elia et al. 2018; Izzo et al. 2019), SN 2020bvc (Izzo et al. 2020; Ho et al. 2020a; Rho et al. 2021), and SN 2024gsa (van Dalen et al. 2025; Sun et al. 2024; Srivastav et al. 2025). Of these, SN 2024gsa is particularly notable as the optical counterpart to EP240414a, an FXT also detected by *EP*. There are also several supernovae that show rapid rises, possibly due to early contributions from shock heating or cocoon emission, such as iPTF16asu (Whitesides et al. 2017; Wang et al. 2019) and SN 2018gep (Ho et al. 2019). However, these sources lack a distinct early phase common to the rest of our sample and we therefore do not compare directly here. All of the above sources are Ic-BL supernovae (i.e. the same type as SN 2025kg) with the exception of SN 2008D, which is a Type Ib (Malesani et al. 2009) and therefore likely has a progenitor with a more intact

helium envelope. We also compare to GRB 101225A (Thöne et al. 2011; Campana et al. 2011; Levan et al. 2014), an ultra-long GRB with an early blue component before becoming more consistent with a typical GRB afterglow. In Rastinejad et al. (2025), we extend the comparison to the properties of the supernovae themselves i.e. at later times than examined here.

In Figure 6, we plot the absolute magnitude and colour evolution of these supernovae. In addition, we also fit blackbodies to individual epochs of these supernovae’s early components using the same procedure as detailed in Section 2.1 allowing us to directly compare the temperature, radius and luminosity evolution.

We find that SN 2025kg most closely resembles SN 2006aj and SN 2020bvc. Its blackbody radius, in particular, is in very strong agreement with the early phases of these supernovae although SN 2025kg is somewhat hotter and therefore higher luminosity. There is greater discrepancy with SN 2008D, SN 2010bh, GRB 101225A, SN 2017iuk and SN 2024gsa, although there is difficulty in comparing the latter as there are likely to be overlapping emission components during the early phase (van Dalen et al. 2025; Srivastav et al. 2025; Hamidani et al. 2025b; Zheng et al. 2025). Even accounting for this, however, SN 2024gsa appears to show more rapid radius and luminosity evolution than SN 2025kg but it and both SN 2010bh and SN 2017iuk are somewhat cooler. GRB 101225A’s early optical counterpart is much more luminous but its temperature and radius evolution are somewhat poorly constrained by our methods here. The more in depth modelling of Thöne et al. (2011) indicates a significantly higher temperature but smaller radius, pointing towards a different origin than SN2025kg’s early fast cooling phase.

Finally, while SN 2008D does show a similar slope in its temperature evolution (notably Soderberg et al. (2008) show $T \propto t^{-0.5}$ consistent with our result in Section 4.2), it is much cooler, less luminous and has a smaller radius. This is consistent with a separate origin for the early phase of SN 2008D as a shock breakout from the helium envelope of a Ib progenitor (Soderberg et al. 2008, e.g.) rather than a cocoon or CSM interaction as suggested by our analyses in this work.

In Figure 7, we compare the X-ray light curves of our sample to EP250108a/SN 2025kg, taken either from the references above or acquired from the UKSSDC. Again we find a strong agreement with SN 2006aj and SN 2020bvc - in particular SN2006aj’s light curve is entirely consistent with the observed data and limits from EP250108a. We also find a strong agreement with SN 2010bh/XRF 100316D and while SN 2017iuk/GRB 171205A’s light curve is not particularly well constrained

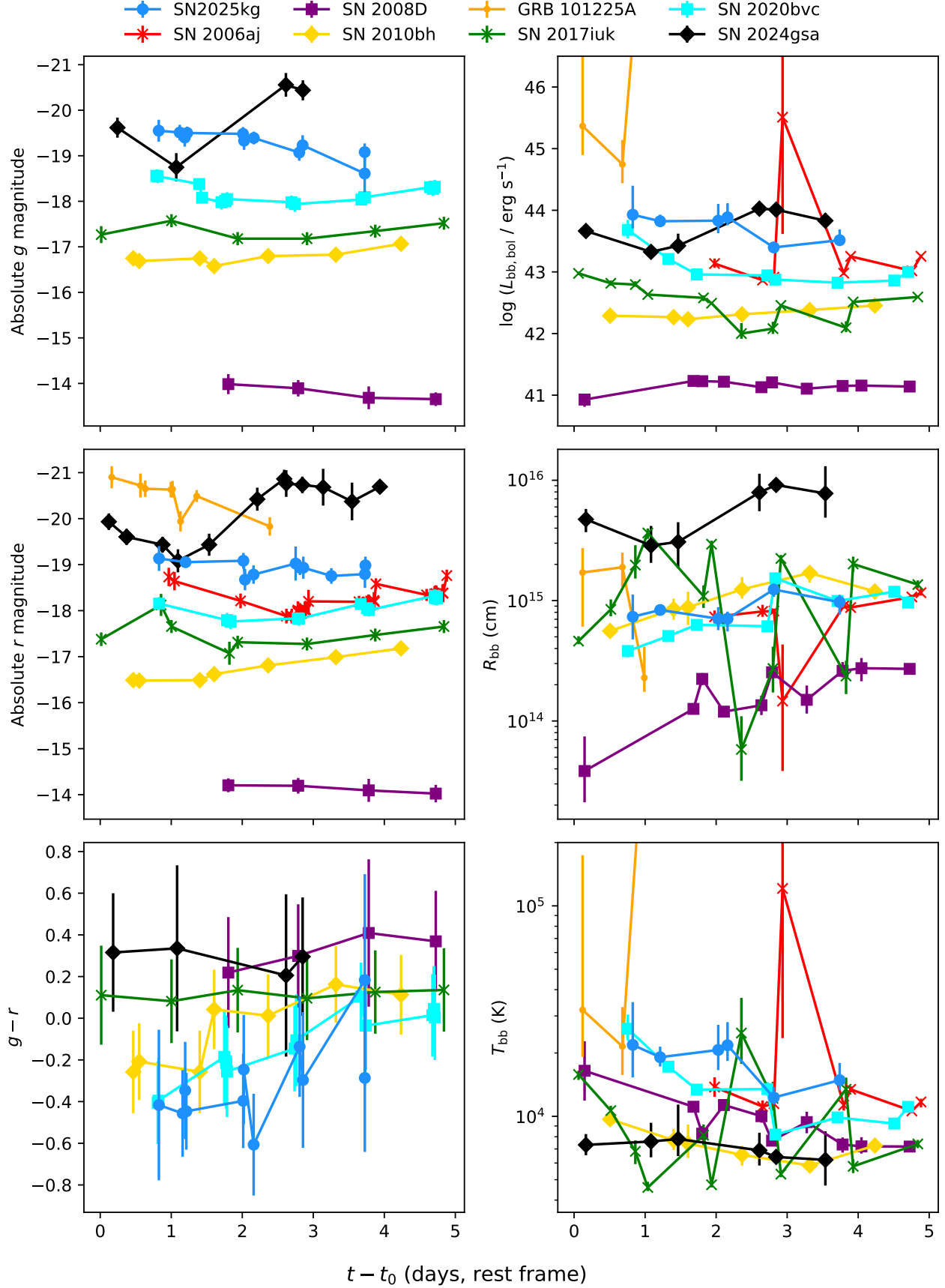


Figure 6. The photometric and blackbody properties of SN 2025kg's fast cooling phase compared to the properties of supernovae with similar early features. We include GRB 101225A which also displays a resemblant feature. In the case of SN 2006aj, we have used the Bessell R filter as a proxy for the r filter.

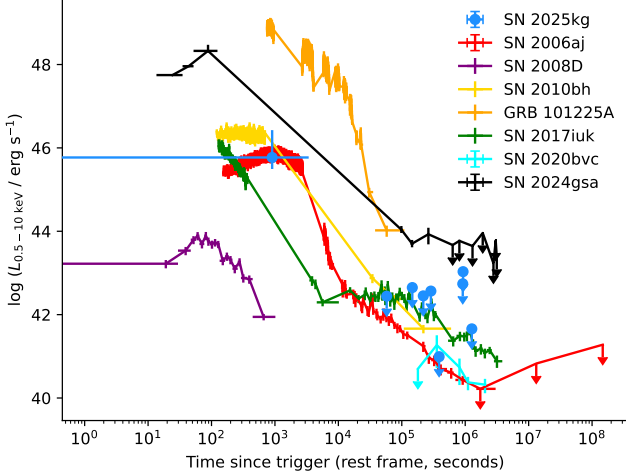


Figure 7. The X-ray light curve of EP250108a compared to our sample of FXT/GRB supernovae. EP250108a is shown in blue.

at early times and hints towards a significantly higher luminosity, it is also broadly compatible. As expected, GRB 101225A and SN 2024gsa are significantly more luminous suggesting either a different origin, e.g. afterglow emission or continued central engine activity in GRB 101225A. Another possibility, which we explore in depth in Section 4, is that while all the X-ray emission in the above cases is powered by some kind of relativistic jet, SN 2006aj, SN 2020bvc and SN 2025kg’s jets are either significantly less powerful or are unable to break out of their progenitor’s outer envelope or the surrounding CSM. Such a jet is deemed to be ‘failed’ (e.g. Nakar 2015; Nakar & Piran 2017; Piro & Kollmeier 2018; Hamidani et al. 2025a) and the resulting high energy emission is much fainter. The material accelerated by the jet may instead form a rapidly expanding cocoon which produces the bulk of the observed emission. SN 2008D is again much fainter as expected from its obviously different origin.

At radio wavelengths and including the limits from Schroeder et al. (2025) and An et al. (2025), we find SN 2025kg is again compatible with SN 2020bvc (Ho et al. 2020a) and SN 2006aj’s radio counterparts (Soderberg et al. 2006). This is consistent with a picture where all of these events either had similar weak or failed jets or, as suggested elsewhere (e.g. Cobb et al. 2006; Toma et al. 2007; Emery et al. 2019), were observed at least somewhat off-axis. In contrast, SN 2017iuk and SN 2024gsa are significantly brighter in radio than SN 2025kg, again suggesting that if they had emerged from a similar progenitor system, a powerful jet successfully broke out. We are unable to compare to SN 2010bh due to a lack of data.

To summarise, we find SN 2025kg to be similar to SN 2006aj and SN 2020bvc suggesting both that a similar progenitor powered all these events and that the environment surrounding the explosion was similar. In particular, it is likely that if there were jets, they were either relatively low energy and/or failed to break out. There are also some similarities to SN 2017iuk and SN 2024gsa but these particular events were more likely to have successful jets. In particular, SN 2024gsa is significantly more luminous at both X-ray and radio energies. SN 2017iuk, on the other hand, is roughly compatible in X-rays with SN 2025kg but its radio is much brighter, suggesting this could be a case of a somewhat off-axis but successful jet. The resemblance between SN 2010bh and SN 2017iuk also suggests a similar nature for the former. The additional optical component in SN 2024gsa may arise due to the presence of both cocoon and dense-CSM emission (van Dalen et al. 2025) or could be the result of a more successful jet (Hamidani et al. 2025b; Zheng et al. 2025). On the other hand, both GRB 101225A and SN 2008D show significant differences to SN 2025kg, however, and are likely to be the result of substantially different systems.

As explored in Rastinejad et al. (2025), the supernovae themselves in SN 2006aj, SN 2020bvc, SN 2024gsa and SN 2025kg also show distinct similarities that further tie these events together and suggest similar origins.

4. THE NATURE OF EP250108A/SN 2025KG

4.1. Energetics

To explore the origins of EP250108a/SN 2025kg, we first evaluate the observed energetics. At the luminosity distance of EP250108a, the flux reported by Li et al. (2025c) equates to a luminosity of $5.9^{+20.9}_{-2.8} \times 10^{45}$ erg s^{-1} and the 2200 s assumed duration of the FXT implies a total isotropic equivalent energy of $1.3^{+4.6}_{-0.6} \times 10^{49}$ erg in the 0.5 to 4 keV band. Ravasio et al. (2025) also place constraints on higher energy emission using the Gamma-ray Burst Monitor (GBM) instrument on the *Fermi* satellite. In the 10 to 1000 keV band, any emission is limited to an isotropic equivalent luminosity $\lesssim 2.4 \times 10^{48}$ erg s^{-1} .

The energy is therefore \sim two orders of magnitude lower than the bulk of the long GRB population (e.g. Nava et al. 2012). If we implicitly assume that the jet did break out but did not produce gamma-rays in our observable window (Ravasio et al. 2025), we can constrain the luminosity of such a jet. Only bursts with peak isotropic-equivalent gamma-ray luminosities under $\sim 10^{49}$ erg s^{-1} are viable, leaving only low-luminosity GRBs (e.g. Liang et al. 2007; Virgili et al. 2009). These GRBs are significantly lower luminosity than the major-

ity of the population and often have softer prompt emission (Patel et al. 2023). The reasons for the stark differences between these sources and other GRBs are not entirely clear but one possibility is intrinsically weaker or possibly failed jets (e.g. Nakar 2015; Senno et al. 2016) as suggested by our comparison to similar transients.

4.2. Photometric modelling

To fully explore the evolution of SN 2025kg’s fast cooling phase, we first fit the full light curve using a simple cooling, expanding blackbody model. While this is primarily a phenomenological model, we can infer the apparent temperature and luminosity evolution. Assuming the photospheric radius broadly coincides with the expanding shock or cocoon and that the resulting emission is thermally dominated⁷, this model also provides some initial constraints on the expansion velocity. As noted above, we are simplifying the presumably complex superposition of various emission components that make up the true SED. However, this procedure is useful for the constraints that can be fed into our other modelling.

We assume the photospheric radius varies as

$$R_{\text{ph}}(t) = R_0 + \int_{t_0}^t v(t) dt, \quad (1)$$

where R_0 is the radius of the photosphere at $t_0 = 0.5$ days (rest frame) after the *EP/WXT* trigger time, and $v(t)$ is the expansion velocity,

$$v(t) = v_0 \left(\frac{t + \tau_d}{\tau_d} \right)^{-\alpha_d}, \quad (2)$$

where v_0 is the expansion velocity at $t_0 = 0.5$ days (rest frame) after trigger time, τ_d is a deceleration timescale and α_d is positive. Similarly, the temperature evolution is assumed to vary as

$$T(t) = T_0 \left(\frac{t + \tau_c}{\tau_c} \right)^{-\alpha_c}, \quad (3)$$

where T_0 is the temperature at $t_0 = 0.5$ rest frame days after the *EP/WXT* trigger time, τ_c is a cooling timescale and α_c is positive. We do not include any additional extinction component intrinsic to the host. However, if we do fit for such a component using `dust_extinction` and the Gordon et al. (2024) averaged model for the Small Magellanic Cloud, we find $A_{V,\text{host}} \sim 0.2$ mag and our other results to be broadly consistent within errors.

We fit this model to SN 2025kg’s light curve using the Markov Chain Monte Carlo (MCMC) algorithm implemented in `emcee v3.1.6` (Foreman-Mackey et al. 2013)

with 32 walkers. We use 5000 iterations, discarding the first 500 as burn-in, and include an additional parameter f representing the fractional underestimation of our errors⁸. We summarise our priors in Table 2.

As shown in Figure 8, we find this model is a reasonable representation of the light curve in the fast cooling phase and give our inferred parameters in Table 2 and show the corner plot in Figure 14. The inferred temperature, radius and bolometric luminosity evolution of the fast cooling phase are shown in Figure 9 and are in good agreement with the values inferred from blackbody fits to the photometric epochs and our spectroscopic observations (see above). We note that the model slightly underpredicts the *g* band and overpredicts the UV bands (*u*, *uvw1*, *uvm2* and *uvw2*). This is likely due to us neglecting the effect of increasing opacity as heavy elements are formed in the rising supernova, an effect modelled in detail below, and possibly due to underestimating the deceleration of the photosphere at late times (see top right panel of Figure 9).

Our results also indicate that the initial expansion velocity of SN 2025kg was at least mildly relativistic - the inferred R_0 would require an average expansion velocity over the first 0.5 rest frame days of $\sim 1.3 \times 10^{10}$ cm s⁻¹ or $\sim 0.45c$. However, this is inconsistent with a simple extrapolation of the inferred velocity evolution. This suggests the early expansion velocity is much faster before rapidly decelerating to match the value inferred at 0.5 days. To constrain this further, we repeat our fit with v_0 , R_0 and T_0 as the expansion velocity, radius and temperature at the trigger time. We fix $R_0 = 10^{12}$ cm, i.e. the largest radius expected for the presumed Wolf-Rayet progenitor and find $v_0 \sim 0.6c$. This is maintained for \sim eight hours before a rapid deceleration. We note, however, that this fit is an extrapolation of later data and the velocity and temperature evolution are significantly more complex than we have assumed.

We can however compare the *EP/WXT* data with the prediction from this model of a soft, thermal X-ray source at the trigger time. Such a source is inconsistent with the harder observed spectrum of the transient (Li et al. 2025c,d), indicating a different origin for the X-ray and early optical emission. We explore this further in Sections 4.3 and 4.5.

4.3. Origin of the X-ray emission

Having established that the same thermal transient is unlikely to generate both the X-ray and optical emis-

⁷ Or is at least quasi-thermal.

⁸ f enters into our likelihood function as an additional factor of $F_{\nu, \text{model}} e^{\log f}$ added in quadrature to the measured errors.

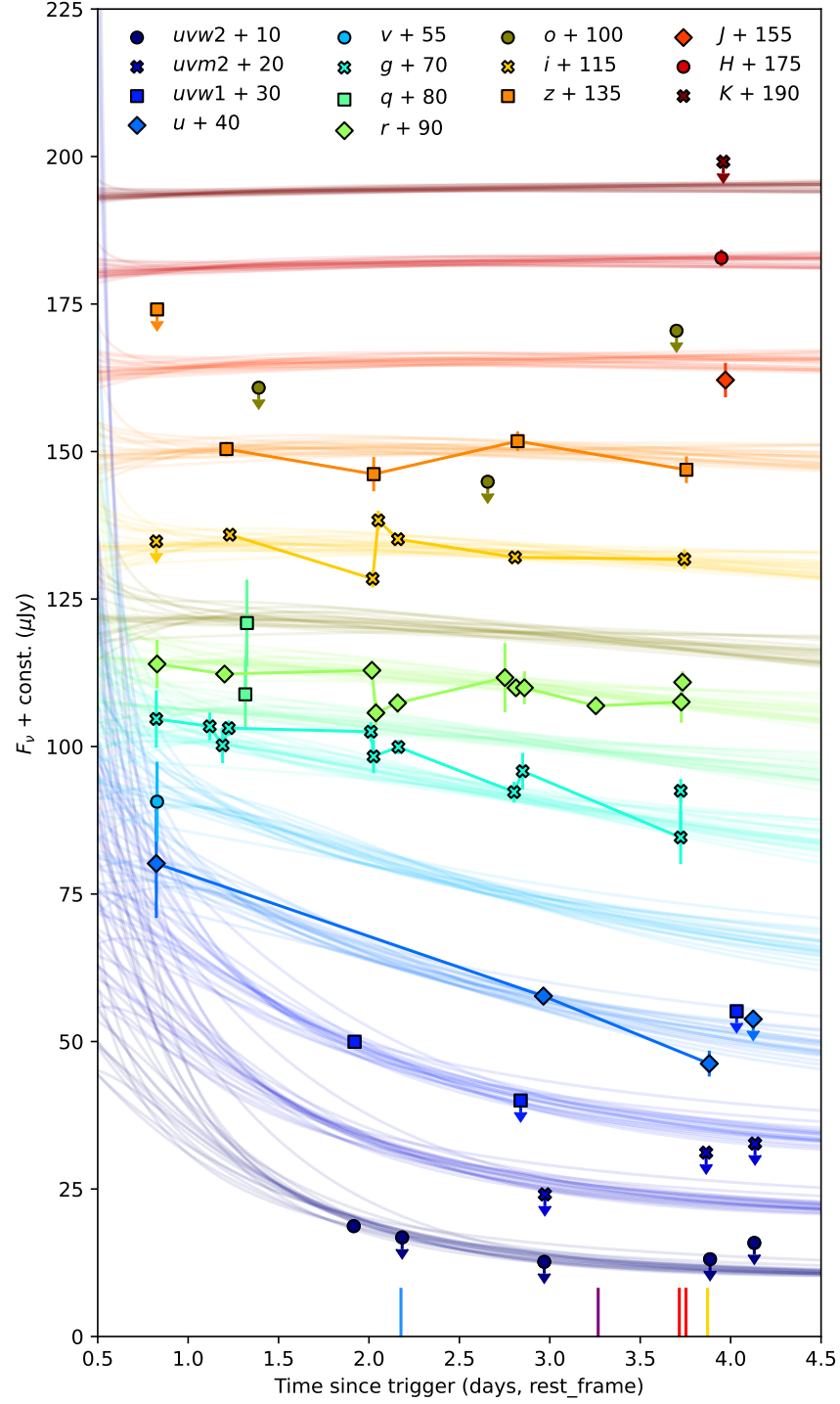


Figure 8. The UVOIR light curve of SN 2025kg's fast cooling phase fitted with our cooling, expanding blackbody model. We show traces from 20 randomly selected fits in our MCMC chain. The vertical lines indicate the times of our spectroscopic observations (with colours corresponding to Figure 4).

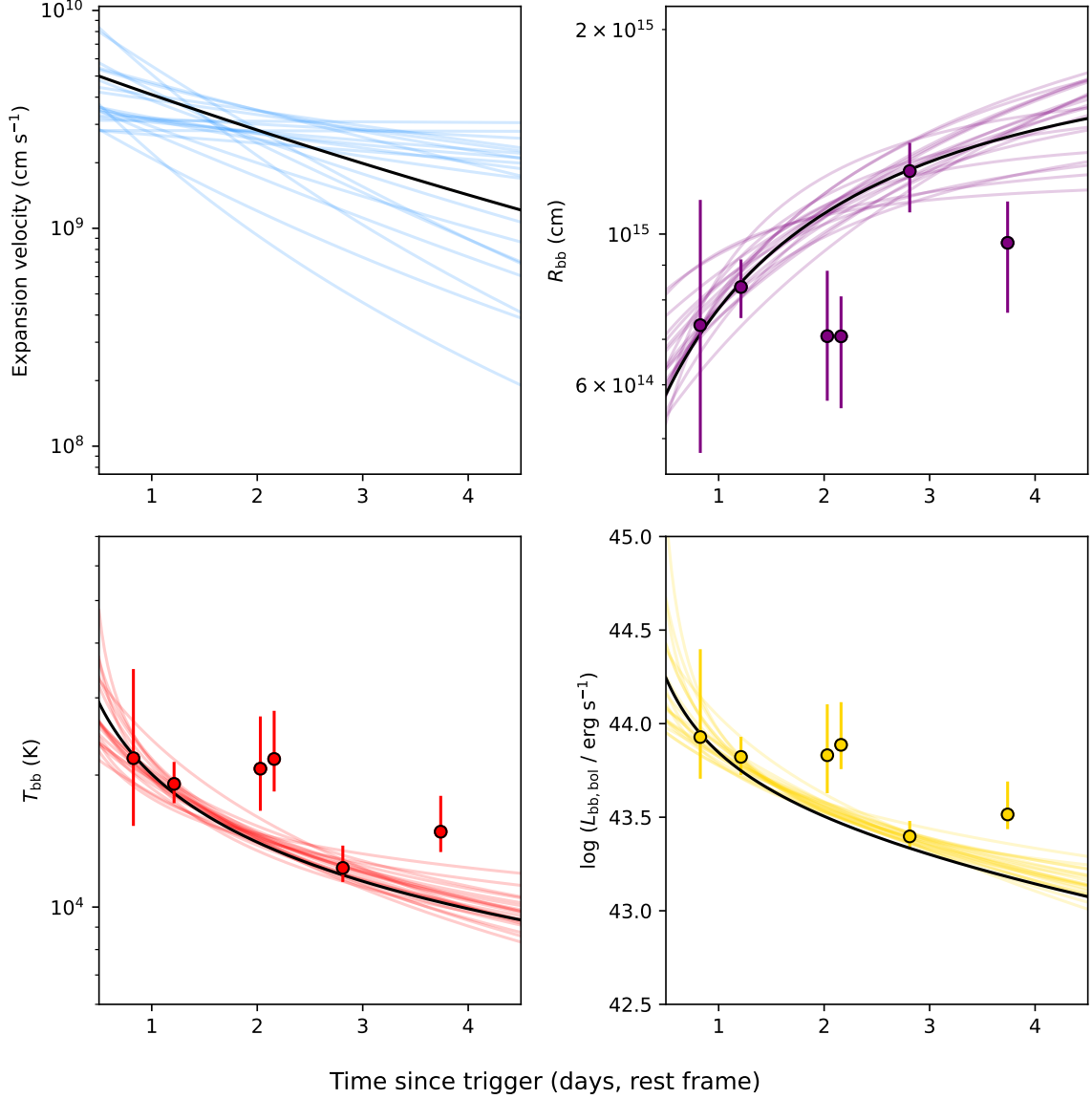


Figure 9. The velocity, radius, temperature and luminosity evolution of SN 2025kg's fast cooling phase inferred from our cooling, expanding blackbody model with traces from the same fits as in Figure 8. The black lines in each panel indicate the evolution derived when using the median of each parameter (i.e. the values reported in Table 2). We also plot the properties inferred from our blackbody fits to our photometric epochs (circles) and spectroscopic continua (crosses).

Table 2. The priors and inferred values from our fit to SN 2025kg’s fast cooling phase light curve with our cooling, expanding blackbody model.

Parameter	Prior	Fitted value
R_0	$> 1 \times 10^{12}$ cm	$5.81_{-1.06}^{+1.46} \times 10^{14}$ cm
v_0	$0.0 < v_0 < c$	$5.00_{-1.81}^{+2.58} \times 10^9$ cm s $^{-1}$
τ_d	> 0.0 s	$1.32_{-0.87}^{+3.44} \times 10^6$ s
α_d	$0.0 < \beta < 10.0$	$6.10_{-3.28}^{+2.85}$
T_0	> 0.0 K	$2.92_{-0.59}^{+1.25} \times 10^4$ K
τ_c	> 0.0 s	$3.79_{-2.46}^{+6.21} \times 10^4$ s
α_c	$0.0 < \alpha < 1.0$	$0.49_{-0.13}^{+0.21}$
f	$-10.0 < \log f < 1.0$	$-2.00_{-0.19}^{+0.18}$

sion, we now investigate the source of the FXT itself. The luminous X-ray signal can be explained through Bremsstrahlung emission arising from a large mass of material moving at a high velocity. From the massive star progenitor of EP250108a, this could be from either shock heating in the supernova blastwave or the propagation of a failed jet through the star or clumpy stellar wind. Here, we use the framework developed in Fryer et al. (in prep) to explore these possibilities.

The fastest ejecta is described by a distribution of velocities and the combined emission from this distribution produces the observed X-rays. For the energy distribution of high-velocity ejecta, we use a simple power-law:

$$E(\Gamma\beta) \propto (\Gamma\beta)^{-p} \text{ for } \Gamma < \Gamma_{\max} \quad (4)$$

$$= 0 \quad \text{otherwise}$$

where Γ is the Lorentz factor, β is the velocity divided by the speed of light and p describes the velocity distribution. We explore two different engine scenarios known to power massive star explosions. The first is a convective engine where the core collapse results in a hot proto-neutron star (e.g. Woosley 1993; Herant et al. 1994) and is expected in the vast majority of core collapse supernovae. The neutrino luminosity of the remnant drives a blastwave which generates a relativistic component ($\Gamma_{\max} \sim 2$) from shock acceleration as it exits the star. The second is a collapsar engine where the star explodes through a combination of disk winds and collimated jets. This engine was invoked to explain long GRBs and their associated Ic-BL supernovae (MacFadyen & Woosley 1999; Woosley & Bloom 2006) and may also explain other Ic-BLs (Fryer et al. 2024). In this case, the jet fails to efficiently break out of the star’s outer envelope or CSM and the resulting ejecta is a semi-relativistic cocoon ($\Gamma_{\max} \sim 5 - 10$) of a baryon-loaded

jet ejecta. For this failed jet model, we assume the velocity distribution is relatively flat ($p = 0 - 0.5$). For the convective engine, we use steeper slopes ($p \sim 2 - 4$) to match shock acceleration as the blastwave breaks out of the star (Tan et al. 2001).

We find that we can reproduce the peak luminosity, half-peak duration and the rapid decay with both convective and jet-driven models under certain parameters. We show several such models in Figure 10 and can use the parameters inferred from this modelling to place lower limits on the mass moving at high velocities. For our jet driven model, matching the observed X-ray data requires roughly $10^{-4} - 10^{-3} M_{\odot}$ of ejecta with velocities above $0.1c$. This is consistent with recent calculations of the breakout of the jet-driven cocoon (Gutiérrez et al. 2024b). For our convective engine model with a shallow power law ($p = 2$), we are able to fit the data only if we assume the high velocity ejecta ($\beta > 0.1$) exceeds $1 M_{\odot}$. We can reduce this requirement by more than an order of magnitude (down to $0.04 M_{\odot}$) by flattening the velocity distribution ($p \sim 1$). For the convective engine, the energy is limited to two to three times the energy at the launch of the explosion. For current SN progenitor models, the total explosion energy is limited to $\sim 1 - 3 \times 10^{51}$ erg (Fryer & Kalogera 2001). Although long-lived engines can increase the total energy by a factor of ~ 2 , most convective-driven engine simulations have comparable energies to the explosion energy. These models are expected to have less than $0.001 - 0.01 M_{\odot}$ of ejecta at the required high ($\beta > 0.1$) velocities (Fryer et al. 2018). We can therefore only produce X-ray signals that match the observations in an extreme case where we both assume supernova energies exceeding current models and push the limits of the mass/energy distribution with ejecta velocity.

We can further constrain the shock interaction conditions by following the evolution of our fast-moving ejecta in the first few days and, in particular, the velocity of the photosphere. The progenitors of Ic supernovae can eject material from their outer envelope as they approach core collapse in the form of stellar winds (e.g. Dessart et al. 2020). As the ejecta propagates through this stellar wind, it will sweep up mass and decelerate. At the same time, as it becomes optically thin, the photosphere recedes relative to the outflowing ejecta, thus probing slower-moving inner material. To calculate the photospheric velocity, we assume the mass of the circumstellar medium is set by a wind profile, the enclosed mass out to radial extent R is:

$$M_{\text{wind,enclosed}}(R) = (\dot{M}_{\text{wind}}/v_{\text{wind}})R \quad (5)$$

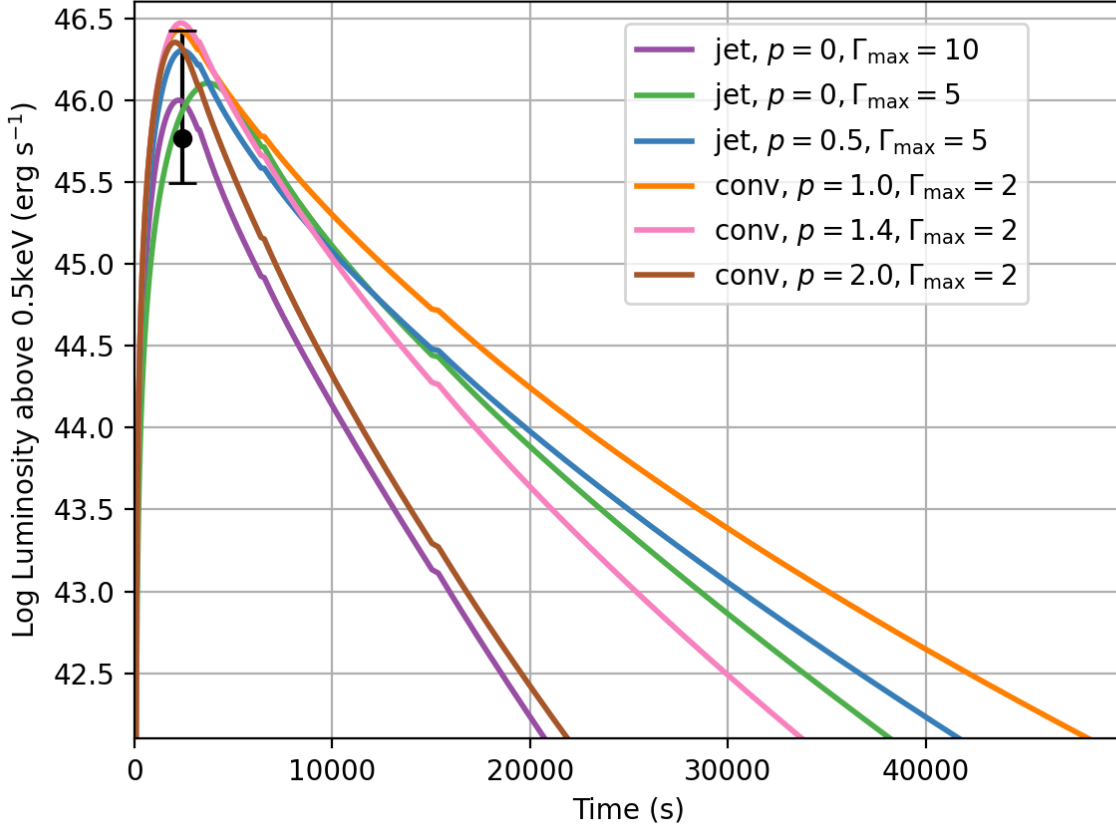


Figure 10. X-ray luminosities as a function of time from the high-velocity, high-velocity ejecta. Here we assume two basic models: a convective engine where the high-velocity ejecta is produced as the shock propagates out of the stellar edge, and a jet-driven model where the high-velocity is dictated by the failed jet + cocoon ejecta. These models are differentiated by the distribution (mass as a function of ejecta velocity) and the maximum Lorentz factor of the ejecta.

where \dot{M}_{wind} is the wind mass loss rate, $v_{\text{wind}} \approx 1000 \text{ km s}^{-1}$, and R is the radial extent. As discussed below, our optical light curves require strong shock interactions at early times (either a shell or a strong wind). For this calculation, we assume a strong wind: $\dot{M}_{\text{wind}} = 10^{-4} M_{\odot} \text{ yr}^{-1}$. We approximate the expansion velocity by applying momentum conservation, decelerating the fastest moving material and moving inward as the high-velocity blastwave propagates through the circumstellar medium. This rapid deceleration (and deposition of this high-velocity material) is required in our SN calculations to explain the optical emission (see Section 4.2). By also including a simple gray opacity, we can calculate the position of the photosphere (optical depth ~ 1) and the velocity at that photosphere. Figure 11 shows this photospheric velocity evolution with time for our best-fit X-ray models (both jet-driven and convective engines) from Figure 10. Although the photospheric velocity in our convective-engine model is ini-

tially slower, the larger high-velocity ejecta mass means that it decelerates slowly with time and therefore the velocity is too high to match the data at a day or so (see Section 4.2). In comparison, the low-mass jet-driven models do decelerate sufficiently quickly. We thus conclude this event is most likely powered by a collapsar engine, with the explosion driven by an accretion disk and jet. The rapid drop-off in the X-ray luminosity at late-times provides a final constraint on the jet-driven models. A fraction of these models have X-ray luminosities in excess of $10^{43} \text{ erg s}^{-1}$ at 10^5 s , inconsistent with the observed limits, and we therefore exclude them. We next explore whether we can constrain whether the jet successfully broke through the star/CSM.

4.4. Constraints on jet/ejecta behaviour

Having shown how a jet driven engine can produce the X-ray emission observed by *EP*, we further examine the constraints on its behaviour from other observa-

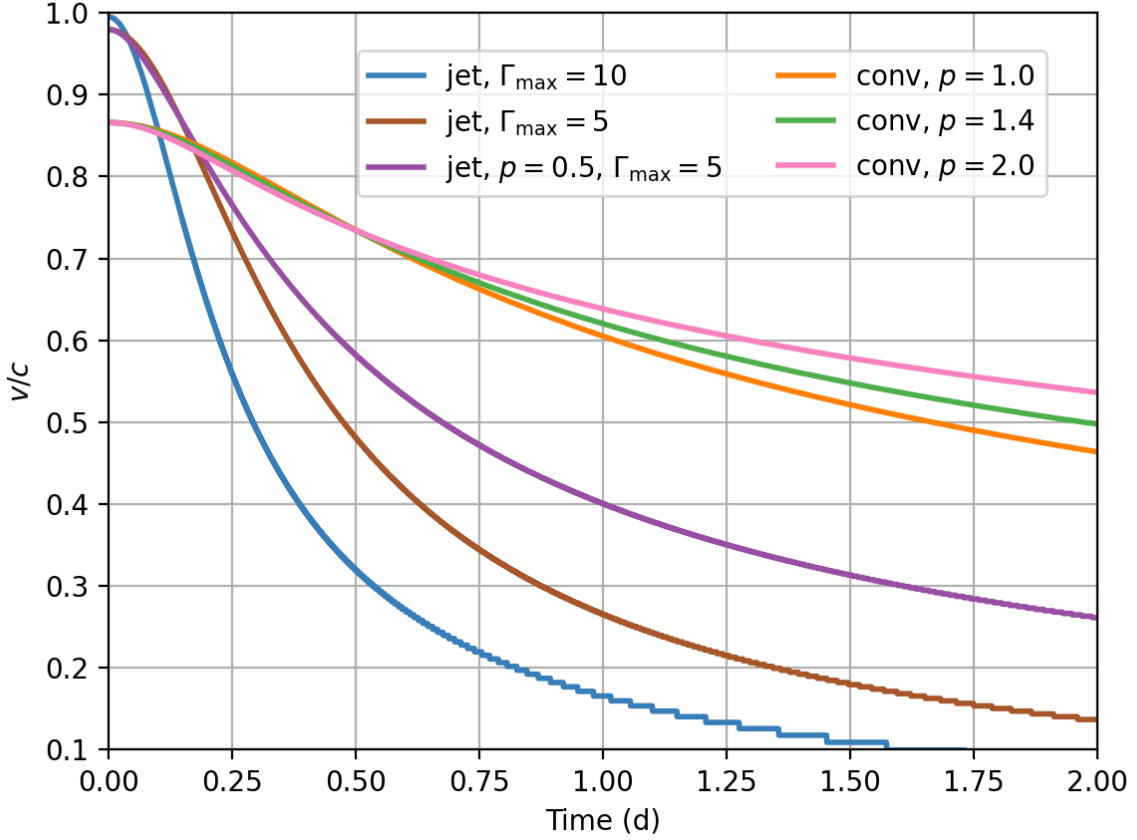


Figure 11. Model photospheric velocity of the shock breakout/interaction models from Figure 10. The high mass in the convective-engine models causes them to decelerate slowly, arguing for a high-velocity photosphere in the first 2 days. The lower mass in the jet-driven explosions leads to rapid deceleration of the photosphere.

tions. In addition to the energy limitation from the lack of gamma-ray detections (see Section 4.1), our radio observations also provide some constraints on the presence of any other fast-moving ejecta.

In Fig. 12, we show the predicted radio light curves for different parameters for jets viewed on-axis and 20° and 50° off-axis in first, middle, and last panels, respectively. All models assume a ‘tophat’ jet following JETSIMPY (Wang et al. 2024) using REDBACK (Sarin et al. 2024). We note that these models do not include synchrotron self-absorption. However, this, or using a structured jet instead of a tophat, does not appreciably impact our interpretation, as the dominant uncertainty is from the parameters themselves. The black arrows indicate upper limits from our radio observations at 3.06 GHz, while the different colours indicate different assumptions about the jet parameters. The ‘fiducial’ model shown in red shows the radio afterglow at 3.06 GHz of a $10^{51.5}$ erg kinetic energy jet with an initial Lorentz factor of 1000 and $\theta_j = 10^\circ$, trav-

elling into a wind-medium with ISM density following $n_{\text{ism}} = A \left(\frac{r}{10^{17} \text{cm}} \right)^{-2}$ where $A = 1 \text{ cm}^{-3}$, i.e., the density at a radius of 10^{17}cm , with typical values for microphysical parameters $p = 2.17$, $\epsilon_e = 0.1$, and $\epsilon_B = 0.01$. Different colours indicate different assumptions from this fiducial model, with the pink curve representing light curves from a constant density ISM with no wind. Our radio observations can confidently rule out jets with kinetic energies $\gtrsim 10^{51}$ ergs in a wind-like medium, even for far-off-axis scenarios, with the only viable solution where such a jet has a low initial Lorentz factor (~ 2) and also observed at least 50° off-axis (green curves in last panel). Our non-detections cannot rule out on- or off-axis jets weaker than 10^{50} ergs propagating into a low-density ISM.

The radio limits from Srinivasaragavan et al. (2025) and Li et al. (2025d) are also broadly consistent with our results. Srinivasaragavan et al. also model possible afterglows but assume a constant density medium as opposed to the wind medium we assume here. They also

conclude a low energy on-axis jet is plausible, but suggest that higher energy off-axis jets may also be possible and would be expected to peak at late times.

While the above only considers jets, our results are broadly applicable to any quasi-spherical outflow such as the fast-ejecta from the supernova as implied by our X-ray modelling above. We do note, however, that our constraints are inconsistent with the slowly coasting jet suggested by Li et al. (2025d) to explain the early optical emission.

4.5. Origin of the early optical emission

Our blackbody analyses show that we can broadly match the optical emission with a fast-moving, cooling blackbody. Here, we explore more physically-motivated models. The broad similarity of our light curves to past GRBs and supernovae e.g. SN2020bvc, provides some hints towards the appropriate models, i.e. some form of shock breakout and cooling from supernova ejecta expanding out into a dense CSM. This could be the envelope of the star, eruptive mass-loss in the years leading up to the supernova, or winds from the progenitor.

We explore these different scenarios further by fitting the data for $t \leq 6.5$ d with models for shock cooling (Piro et al. 2021) and dense-CSM shell shock cooling (Margalit 2022) implemented in REDBACK (Sarin et al. 2024) using the PYMULTINEST (Buchner et al. 2014) via BILBY (Ashton et al. 2019). We fit assuming a Gaussian likelihood with a systematic error added in quadrature to the statistical errors on all data points i.e., $\sigma_i^2 = \sigma_{i,\text{data}}^2 + \sigma_{\text{sys}}^2$, where the first term is the original error on our data points and $\sigma_{\text{sys}} = 0.15$ is a systematic uncertainty to capture any discrepancies caused by differences in photometric reduction or filter transmission curves, and broad uniform priors. We also assume the contribution from the supernova to be relatively negligible at this time as there is little evidence of plateauing or rising in the light curve. In addition, the uncertainties in the models themselves are notably larger than the possible supernova contribution. We note the key difference between the models we investigate here is the assumed profile of the CSM, with the Piro et al. (2021) model assuming a broken power law density profile aimed to resemble homologous expansion of material following shock breakout from the star (e.g., Matzner & McKee 1999), while the later assumes a CSM shell located at initial radius, R_0 of width ΔR_0 with a sharp drop in density at larger radii, with further differences in the treatment of radiative diffusion (Margalit 2022).

Both models capture the evolution of the light curve, however, the estimated parameters from the shock cooling model (Piro et al. 2021) are inconsistent with expec-

tations and our analysis of the X-ray emission, such as the overall energetics and velocities. In particular, our inference with this model suggests $\geq 10^{52}$ erg of energy and a total CSM mass of $\geq 6M_\odot$. We note that this is significantly larger than that found by Srinivasaragavan et al. (2025), likely due to them including an additional supernova contribution in their fit. In contrast, the dense-CSM model provides more reasonable estimates consistent with the X-ray, with a CSM mass of $0.2 - 0.9M_\odot$, with a kinetic energy of $\lesssim 10^{51}$ erg with $R_0 \sim 7 \times 10^{14}$ cm and a shell width of $\sim 0.3R_0$. Our results suggest that if the light curve is powered by some form of CSM interaction, the CSM has an abrupt drop in density to adequately describe the light curve and be consistent with inferences from the X-ray observations. We note that while the model formally assumes the presence of a shell at R_0 , the model is also compatible with the assumption of a wind, provided the wind is truncated at $r > R_0$. This provides some clues into the progenitor and perhaps a binary companion (as the CSM need not be from the progenitor of EP250108a), requiring either eruptive mass-loss in the years leading up to the supernova that could place a dense-CSM shell at $R_0 \sim 10^4 R_\odot$ or a wind profile that terminates at such a radius.

Motivated by our X-ray analyses, which suggest that jet-driven models are most likely, we also explore a shocked cocoon/failed GRB-jet model. We broadly follow the models for shocked cocoon emission outlined Nakar & Piran (2017) and Piro & Kollmeier (2018). In particular, we assume a GRB jet of negligible mass propagates out through ejecta of total mass M , with a mass profile which follows a power-law distribution i.e.,

$$m(> v) = M \left(\frac{v}{v_0} \right)^{-(s+1)}, \quad (6)$$

where v_0 is the minimum velocity of the ejecta, and s is the power-law exponent of the energy distribution with respect to velocity. The energy provided by this interaction is $E \propto \frac{mvR}{t}$ where t is time, while the luminosity is $\approx E(t)/t_{\text{diff}}$ where t_{diff} is the characteristic diffusion timescale. We fit this model using REDBACK with the same likelihood and data treatment as described above, further assuming that the shocked ejecta is confined to some angle θ_{cocoon} . Our fits to the light curve are shown in Fig. 13. We infer that the cocoon contains $\sim 0.04 - 0.15M_\odot$ of shocked ejecta, confined to $\sim 20 - 25^\circ$, with a kinetic energy of $\sim 4 - 45 \times 10^{50}$ erg, with a shock radius of $\sim 1.9 - 3.5R_\odot$. This model provides a good fit to the data, and our parameters are broadly in agreement with inferences from the X-ray observations and the constraints from the radio observa-

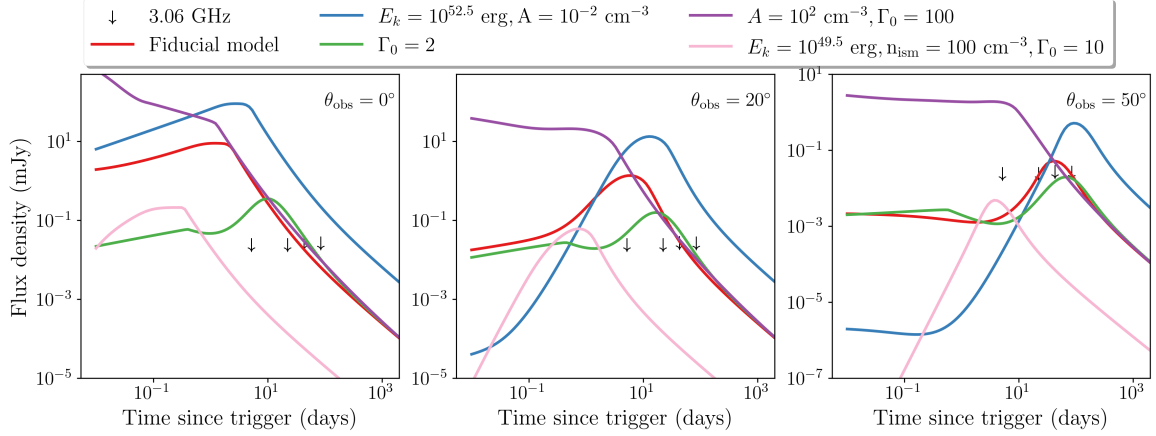


Figure 12. Radio afterglows at 3.06 GHz following a ‘top hat’ jet for different assumptions over the ‘fiducial model’ indicated by the red curves. The three panels correspond to different observer viewing angles while the arrows indicate upper limits from our radio observations.

tions above. They are also consistent with the results of [Srinivasaragavan et al. \(2025\)](#) who fit a similar model. While we cannot definitively rule out whether any jet successfully broke out, the inferred energetics from our modelling above, the radio and X-rays constraints suggest that if EP250108a/SN 2025kg was jet-driven, either no jet broke out or was weaker than $\approx 10^{51}$ erg. We note that here, we only considered the thermal emission from the shocked cocoon. Such shocked cocoons are also expected to produce non-thermal emission as discussed earlier in Sec. 4. However, this is extremely sensitive to assumptions about microphysical parameters and the quantity of fast ejecta, which our modelling here does not constrain.

5. CONCLUSIONS

In this Letter, we have detailed our observations and analysis of the fast cooling phase of EP250108a/SN 2025kg, comprising the first ~ 6 days of data. We have also used X-ray and radio data from later times to further investigate the transient. The remaining data from our campaign and its analysis are presented in [Rastinejad et al. \(2025\)](#) which examines the properties of the supernova itself in much greater detail. We summarise our conclusions below:

- SN 2025kg’s early evolution shows distinct similarity to similar behaviour in the broad line Ic SN 2006aj and SN 2020bvc suggesting these events arise from similar progenitor systems. There are also similarities to early features in other broad line Ic supernovae SN 2017iuk and possibly SN 2024gsa. In our companion paper, [Rastinejad et al. \(2025\)](#), we show the properties of the supernovae themselves in SN 2006aj, SN 2020bvc and SN 2024gsa are also similar.

- We find that the optical transient is consistent with an expanding, cooling blackbody similar to several other examples in the GRB-SN population, in particular SN 2006aj and SN 2020bvc. We simulate the photometry using this model and find, by extrapolation, an initial expansion velocity of order $\sim 0.4\text{--}0.6c$ that later declines to $\sim 0.1\text{--}0.2c$ by about 0.5 days (rest frame).
- The X-ray emission likely arises from a jet driven engine. To achieve the deceleration and rapid fading required from the observed data, a convection engine would require both extreme supernova energies and masses. However, the low masses required by a collapsar jet engine allow this rapid deceleration and decline in luminosity. The limits set by our radio observations and *Fermi* gamma-ray observations indicate the jet is low energy and/or failed to successfully break out, assuming tophat jets in a wind-medium. We cannot, at this point, constrain whether we are viewing the jet off-axis.
- These results suggest that the optical transient is driven by either shock cooling as supernova ejecta expand into a dense shell of CSM or the jet inferred from the X-rays propagates through the ejecta to produce a shocked cocoon. Both models are consistent with the data and support the suggestion that the jet was low energy or failed to successfully break out. Our conclusions are consistent with the findings of [Srinivasaragavan et al. \(2025\)](#) and [Li et al. \(2025d\)](#). In [Rastinejad et al. \(2025\)](#), we further discuss the progenitor system and rates of these failed/weak jet powered FXT-SNe and show that they are likely higher than similar GRB-SNe.

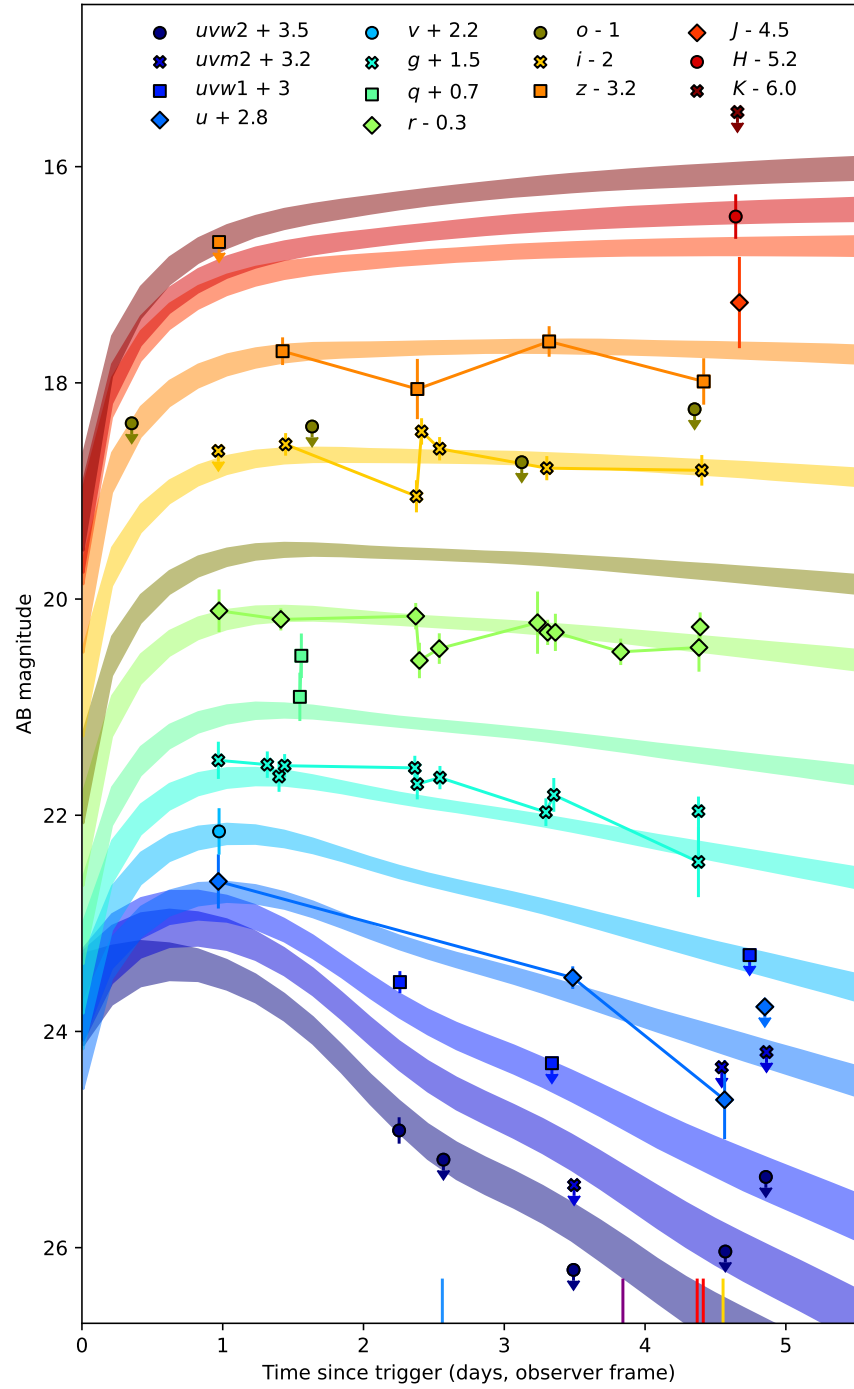


Figure 13. The UVOIR light curve of SN 2025kg's fast cooling phase fitted with a shocked cocoon model. The shaded regions indicate the 68% credible interval of the posterior predictive distribution for each band. The vertical lines indicate the times of our spectroscopic observations (with colours corresponding to Figure 4).

Despite similarities to previous supernova, SN 2025kg is an extraordinary source in terms of both physics and the quality of the data produced by both us and other groups (Srinivasaragavan et al. 2025; Li et al. 2025d). *Einstein Probe* and its unique ability to identify FXTs in real time will allow many more of these rare events to be uncovered and the exact physics underpinning them to be explored.

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nicações (Brazil), and Korea Astronomy and Space Science Institute (Republic of Korea), under programs GN-2024B-Q-107 and GS-2024B-Q-105.

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Facilities: Gemini:Gillett (GMOS-N), Gemini:South (FLAMINGOS2), GTC(OSIRIS), LCOGT (SINISTRO), Liverpool:2m (IO:O), NOT (ALFOSC), Swift (XRT and UVOT), VLT:Melipal (X-shooter)

Software: astropy (Astropy Collaboration et al. 2013, 2018, 2022), dust_extinction (Gordon 2024), emcee (Foreman-Mackey et al. 2013), EsoReflex (Freudling et al. 2013), HEASoft (Nasa High Energy Astrophysics Science Archive Research Center (Heasarc) 2014), photometry-sans-frustration (Nicholl et al. 2023), PIMMS, PyZOGY (Guevel et al. 2021), REDBACK (Sarin et al. 2024)

APPENDIX

A. OBSERVING LOGS

Table 3. The assembled UV, optical and NIR photometry from our observations and other sources. Δt is given in the observer frame and magnitudes are as measured and are not corrected for Galactic extinction.

Date (UT)	Δt (days)	Instrument	Filter	Exposure time (s)	AB magnitude	Reference
2025 Jan 10.77415	2.25299	Swift/UVOT	<i>uvw2</i>	1007.4	21.55 ± 0.07	Revision of Levan et al. (2025a).
2025 Jan 11.08888	2.56773	Swift/UVOT	<i>uvw2</i>	1080.2	> 21.82	This work.
2025 Jan 12.01286	3.49171	Swift/UVOT	<i>uvw2</i>	2053.3	> 22.84	This work.
2025 Jan 13.09120	4.57005	Swift/UVOT	<i>uvw2</i>	1667.2	> 22.67	This work.
2025 Jan 13.37897	4.85782	Swift/UVOT	<i>uvw2</i>	597.2	> 21.98	This work.
2025 Jan 12.01700	3.49584	Swift/UVOT	<i>uvm2</i>	917.4	> 22.37	This work.
2025 Jan 13.06583	4.54467	Swift/UVOT	<i>uvm2</i>	215.0	> 21.28	This work.
2025 Jan 13.38372	4.86257	Swift/UVOT	<i>uvm2</i>	198.8	> 21.14	This work.
2025 Jan 10.77958	2.25842	Swift/UVOT	<i>uvw1</i>	843.9	20.65 ± 0.02	Revision of Levan et al. (2025a).
2025 Jan 11.85942	3.33827	Swift/UVOT	<i>uvw1</i>	251.2	> 21.40	This work.
2025 Jan 13.26392	4.74277	Swift/UVOT	<i>uvw1</i>	67.6	> 20.40	This work.
2025 Jan 09.49019	0.969	MEPHISTO	<i>u</i> ^a	2×180	19.89 ± 0.23	Zou et al. (2025).
2025 Jan 12.00747	3.48631	Swift/UVOT	<i>u</i>	2892.0	20.78 ± 0.03	This work.
2025 Jan 13.08614	4.56499	Swift/UVOT	<i>u</i>	2744.4	21.91 ± 0.35	This work.
2025 Jan 13.37186	4.85071	Swift/UVOT	<i>u</i>	597.2	> 21.05	This work.
2025 Jan 09.41519	0.974	MEPHISTO	<i>v</i>	2×180	20.02 ± 0.19	Zou et al. (2025).
2025 Jan 06.20545	-2.31571	ZTF	<i>g</i>	30	> 21.54	This work.
2025 Jan 09.49020	0.969	MEPHISTO	<i>g</i>	6×50	20.05 ± 0.14	Zou et al. (2025).
2025 Jan 09.83781	1.31665	LT/IO:O	<i>g</i>	1×200	20.09 ± 0.07	Revision of Eyles-Ferris (2025).
2025 Jan 9.920945	~ 1.4	LT/IO:O	<i>g</i>	—	20.20 ± 0.10	Kumar et al. (2025).
2025 Jan 9.96101	1.43985	NOT/ALFOSC	<i>g</i>	2×300	20.10 ± 0.04	Revision of Zhu et al. (2025a).
2025 Jan 10.19027	1.66912	ZTF	<i>g</i>	30	> 19.00	This work.
2025 Jan 10.88571	2.36454	NOT/ALFOSC	<i>g</i>	2×300	20.12 ± 0.05	Malesani et al. (2025).

Table 3 continued

Table 3 (continued)

Date (UT)	Δt (days)	Instrument	Filter	Exposure time (s)	AB magnitude	Reference
2025 Jan 10.90305	2.38189	LT/IO:O	<i>g</i>	6×200	20.27 ± 0.10	This work.
2025 Jan 11.06419	2.54302	VLT/X-shooter	<i>g</i>	3×40	20.21 ± 0.04	This work.
2025 Jan 11.81677	3.29560	NOT/ALFOSC	<i>g</i>	2×300	20.53 ± 0.08	This work.
2025 Jan 11.87469	3.35160	LCO/Sinistro	<i>g</i>	3×300	20.37 ± 0.12	Revision of Izzo (2025).
2025 Jan 12.16815	3.64700	ZTF	<i>g</i>	30	> 19.01	This work.
2025 Jan 12.90017	4.37901	LCO/Sinistro	<i>g</i>	3×300	20.99 ± 0.31	This work.
2025 Jan 12.90049	4.37933	LT/IO:O	<i>g</i>	6×150	20.52 ± 0.09	This work.
2025 Jan 13.18974	4.66859	ZTF	<i>g</i>	30	> 19.63	This work.
2025 Jan 10.06904	1.54788	BlackGEM	<i>q</i>	60	20.25 ± 0.20	This work.
2025 Jan 10.07963	1.55847	BlackGEM	<i>q</i>	60	19.87 ± 0.18	This work.
2025 Jan 09.41519	0.974	MEPHISTO	<i>r</i>	6×50	20.45 ± 0.17	Zou et al. (2025).
2025 Jan 9.93392	1.41277	NOT/ALFOSC	<i>r</i>	3×300	20.53 ± 0.02	Revision of Zhu et al. (2025a).
2025 Jan 10.89215	2.37098	NOT/ALFOSC	<i>r</i>	2×180	20.50 ± 0.07	Malesani et al. (2025).
2025 Jan 10.91841	2.39725	LT/IO:O	<i>r</i>	6×200	20.91 ± 0.13	This work.
2025 Jan 11.05948	2.53831	VLT/X-shooter	<i>r</i>	3×30	20.80 ± 0.10	This work.
2025 Jan 11.75736	3.2362	SAO RAS Zeis-1000	<i>r</i>	8×300	20.56 ± 0.27	Moskvitin et al. (2025).
2025 Jan 11.82939	3.30822	NOT/ALFOSC	<i>r</i>	3×180	20.65 ± 0.06	This work.
2025 Jan 11.88624	3.363	LCO/Sinistro	<i>r</i>	3×300	20.65 ± 0.14	Revision of Izzo (2025).
2025 Jan 12.23224	3.71109	ZTF	<i>r</i>	30	> 19.58	This work.
2025 Jan 12.34830	3.82715	Gemini-North/GMOS-N	<i>r</i>	50	20.83 ± 0.07	This work.
2025 Jan 12.90408	4.38292	LCO/Sinistro	<i>r</i>	3×300	20.79 ± 0.20	This work.
2025 Jan 12.91241	4.39125	LT/IO:O	<i>r</i>	6×150	20.60 ± 0.09	This work.
2025 Jan 13.21237	4.69121	ZTF	<i>r</i>	30	> 19.06	This work.
2025 Jan 08.87477	0.35362	ATLAS	<i>o</i>	3×30	> 19.41	This work.
2025 Jan 10.15593	1.63478	ATLAS	<i>o</i>	4×30	> 19.44	This work.
2025 Jan 11.64527	3.12411	ATLAS	<i>o</i>	6×30	> 19.77	This work.
2025 Jan 12.87307	4.35191	ATLAS	<i>o</i>	4×30	> 19.28	This work.
2025 Jan 14.12614	5.60499	ATLAS	<i>o</i>	3×30	> 19.10	This work.
2025 Jan 09.49020	0.969	MEPHISTO	<i>i</i>	4×79	> 20.66	Zou et al. (2025).
2025 Jan 9.96796	1.44681	NOT/ALFOSC	<i>i</i>	2×180	20.60 ± 0.03	Revision of Zhu et al. (2025a).
2025 Jan 10.89718	2.37601	NOT/ALFOSC	<i>i</i>	2×180	21.08 ± 0.11	Malesani et al. (2025).
2025 Jan 10.93375	2.41259	LT/IO:O	<i>i</i>	6×200	20.48 ± 0.07	This work.
2025 Jan 11.06172	2.54056	VLT/X-shooter	<i>i</i>	3×60	20.64 ± 0.04	This work.
2025 Jan 11.82321	3.30204	NOT/ALFOSC	<i>i</i>	2×180	20.82 ± 0.05	This work.
2025 Jan 12.92426	4.4031	LT/IO:O	<i>i</i>	6×150	20.84 ± 0.10	This work.
2025 Jan 09.49519	0.974	MEPHISTO	<i>z</i>	4×79	> 19.92	Zou et al. (2025).
2025 Jan 9.94647	1.4253	NOT/ALFOSC	<i>z</i>	5×200	20.93 ± 0.08	Revision of Zhu et al. (2025a).
2025 Jan 10.90377	2.3826	NOT/ALFOSC	<i>z</i>	3×200	21.28 ± 0.26	Malesani et al. (2025).
2025 Jan 11.83977	3.3186	NOT/ALFOSC	<i>z</i>	5×200	20.84 ± 0.10	This work.
2025 Jan 12.93758	4.41642	LT/IO:O	<i>z</i>	6×200	21.21 ± 0.19	This work.
2025-01-13 4:35:25	4.67009	Gemini-South/F2	<i>J</i>	3×30	21.77 ± 0.41	This work.
2025-01-13 3:57:32	4.64378	Gemini-South/F2	<i>H</i>	25×15	21.67 ± 0.18	This work.
2025-01-13 4:15:23	4.65618	Gemini-South/F2	<i>K</i>	24×15	> 21.50	This work.

^a The effective wavelengths of the MEPHISTO *u* and *Swift*/UVOT *u* filters are separated by approximately 35Å, in this work we assume them to have the same effective wavelength of 3483 Å.

B. CORNER PLOT

C. SN 2025KG IN RELATION TO LUMINOUS FAST BLUE OPTICAL TRANSIENTS

Another class of transients that also display a blue colour with rapid temperature and luminosity evolution are LFBOTs. Initially, SN 2025kg was suggested to be a

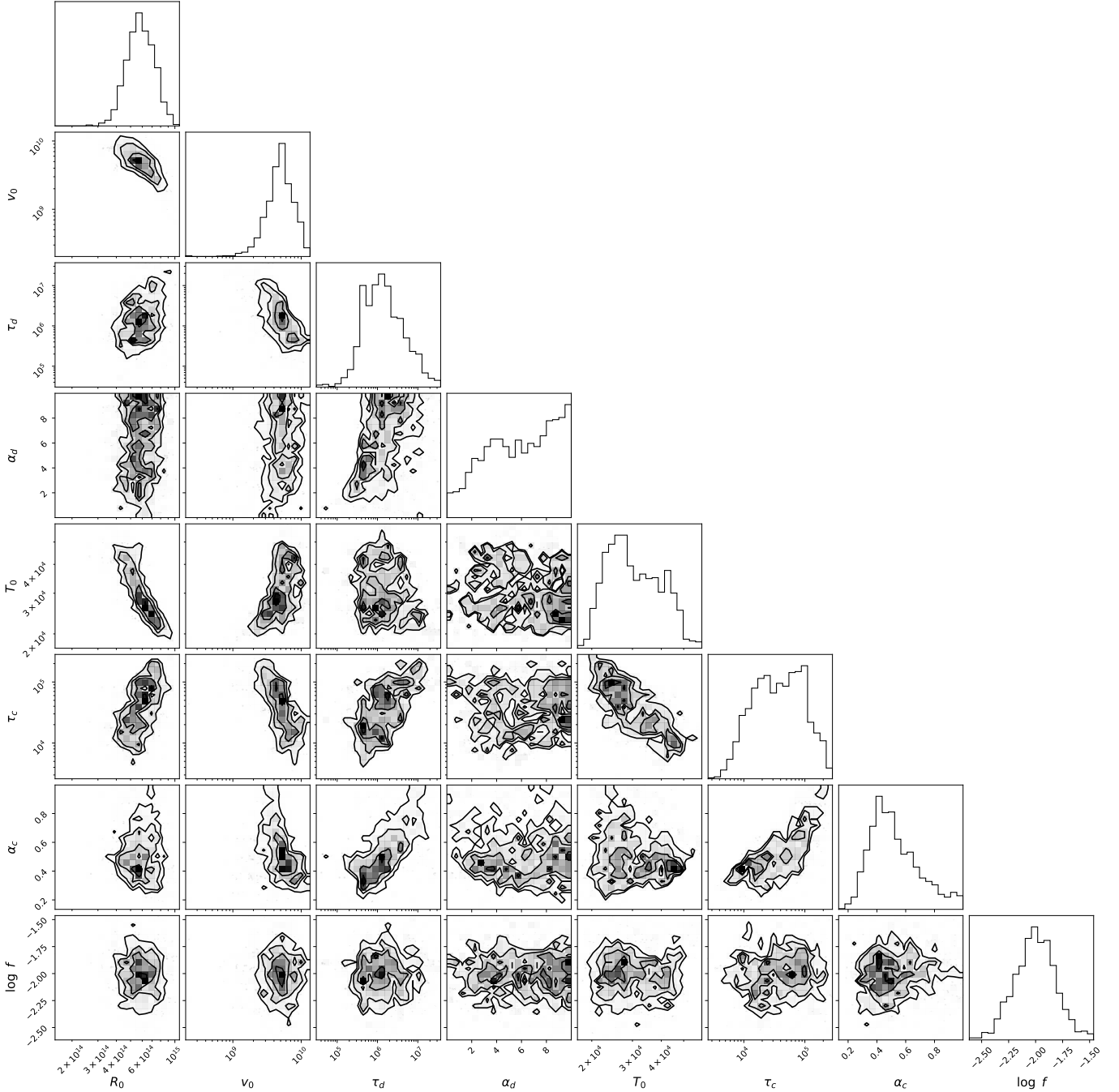


Figure 14. A corner plot showing the parameter covariance in our fit to SN 2025kg’s fast cooling phase with a cooling, expanding blackbody.

member of this class (Zhu et al. 2025b) while a link has also been suggested in the case of the FXT supernova SN 2024gsa (van Dalen et al. 2025). Here we briefly consider the fast cooling phase’s properties in relation to observed LFBOTs.

In Figure 15, we compare the fast cooling phase of SN 2025kg to early data from AT2018cow (Prentice et al. 2018; Margutti et al. 2019; Perley et al. 2019), ZTF18abvkwla (Ho et al. 2020b) and

AT2020xnd/ZTF20acigmel (Perley et al. 2021; Bright et al. 2022; Ho et al. 2022c). Additional examples include AT2020mrf (Yao et al. 2022) and AT2022tsd (Ho et al. 2022b,a; Matthews et al. 2023). Similarly to our supernovae comparison above, blackbodies are fitted to individual epochs of the catalogued photometry using the procedure in Section 2.1.

From Figure 15, it is clear that from the optical properties alone, SN 2025kg is very different to behaviour

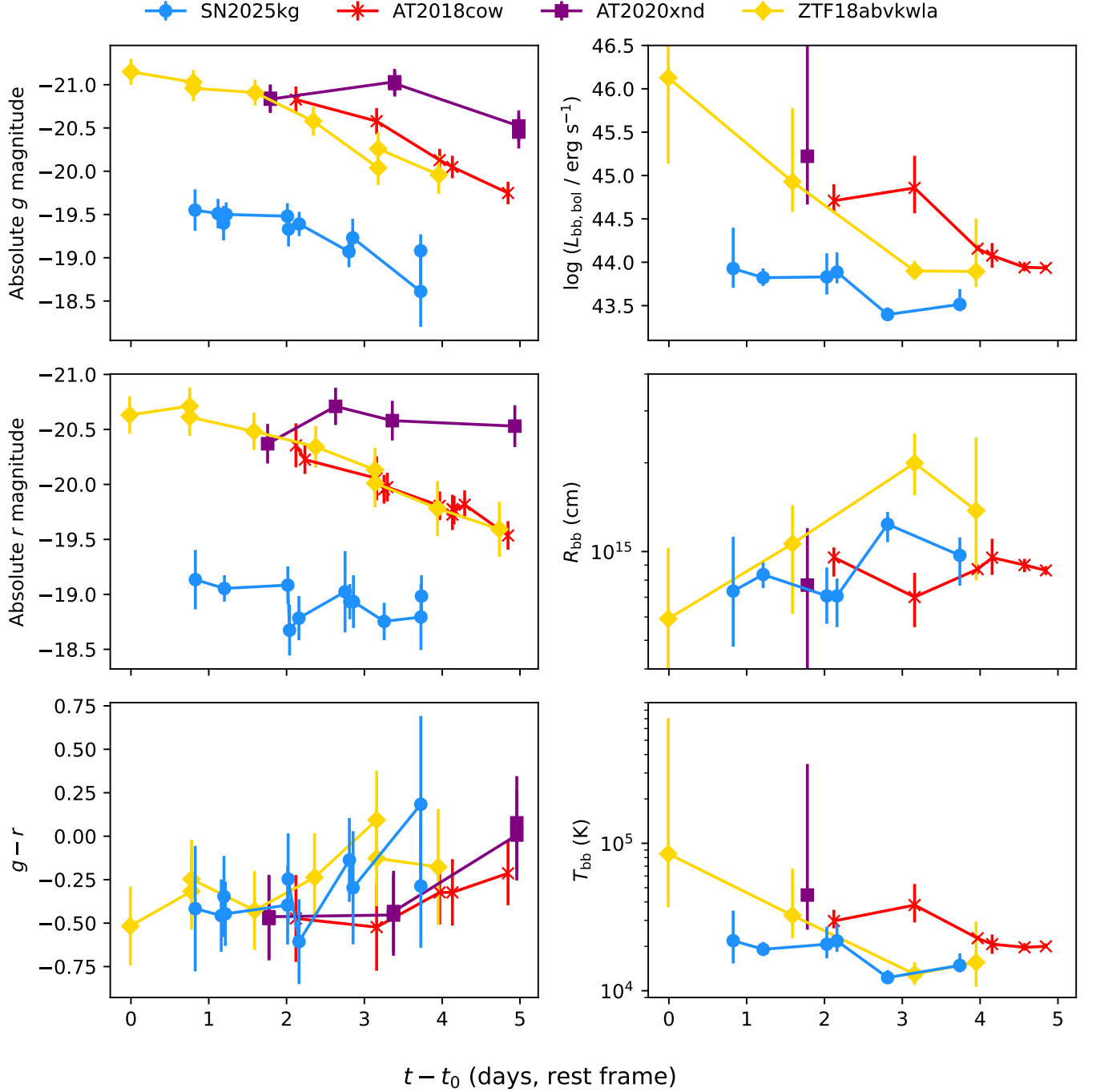


Figure 15. The photometric and blackbody properties of SN 2025kg’s fast cooling phase compared to the early properties of the LFBOTs AT2018cow, ZTF18abvkwla and AT2020xnd. Note that we have taken $t_0 = 58374.41$ MJD for ZTF18abvkwla i.e. the peak time in the g band light curve.

Table 4. The log of our spectroscopic observations. Δt is given in the observer frame.

Date (UT)	Δt (days)	Instrument	Exposure time (s)	T_{bb} (10^4 K)	R_{bb} (10^{15} cm)	$\log \left(\frac{L_{\text{bb,bol}}}{\text{erg s}^{-1}} \right)$
2025 Jan 11.08112	2.56000	VLT/X-shooter	4×600	1.23 ± 0.01	1.13 ± 0.01	43.32 ± 0.01
2025 Jan 12.36373	3.84257	Gemini-North/GMOS-N	3×400	1.17 ± 0.04	1.04 ± 0.05	43.17 ± 0.02
2025 Jan 12.89132	4.37016	GTC/OSIRIS+/R1000R ^a	3×1200	1.24 ± 0.02	1.12 ± 0.02	43.33 ± 0.01
2025 Jan 12.93447	4.41331	GTC/OSIRIS+/R1000B ^a	3×1200	1.24 ± 0.02	1.12 ± 0.02	43.33 ± 0.01
2025 Jan 13.07514	4.55398	VLT/X-shooter	4×600	0.96 ± 0.01	1.34 ± 0.02	43.04 ± 0.01

^a Note that we combine the data from the two GTC/OSIRIS+ observations to produce a single spectrum covering the full wavelength range of both gratings.**Table 5.** The log of our X-ray observations and additional public data observed by *Swift*. Δt is given in the observer frame.

Date (UT)	Δt (days)	Instrument	Exposure time (ks)	$\log \left(\frac{L_{0.5-10 \text{ keV}}}{\text{erg s}^{-1}} \right)$
2025 Jan 10.86591	2.34475	<i>Swift</i> /XRT	2.989	< 42.65
2025 Jan 12.01331	3.49215	<i>Swift</i> /XRT	4.919	< 42.45
2025 Jan 13.12290	4.60175	<i>Swift</i> /XRT	5.139	< 42.57
2025 Jan 14.72557	6.20441	<i>XMM-Newton</i> /pn	30.44	< 40.99
2025 Jan 23.16258	14.64143	<i>Swift</i> /XRT	1.59	< 42.74
2025 Jan 23.32540	14.80424	<i>Swift</i> /XRT	1.248	< 43.03
2025 Jan 28.85781	20.33665	<i>Chandra</i> /ACIS-S3	10.851	< 41.66

Table 6. The log of our radio observations. Δt is given in the observer frame.

Date (UT)	Δt (days)	Telescope	Central frequency (GHz)	Integration time (minutes)	F_ν ($\mu\text{Jy beam}^{-1}$)
2025 Jan 13.74792	5.22676	MeerKAT	3.06	42	24
2025 Jan 30.57014	22.04898	MeerKAT	3.06	42	24
2025 Feb 20.66319	43.14203	MeerKAT	3.06	42	27
2025 Apr 3.39167	84.87051	MeerKAT	3.06	42	26

observed in the LFBOT population. In particular, it is less luminous and cooler than both the prototypical AT2018cow and AT2020xnd. The blackbody radius of SN 2025kg is also somewhat larger and continuing to expand. While Figure 15 only shows the earliest times, both LFBOTs' photospheres were shown to recede. Extending the comparison to other wavelengths, the rapid fading of EP250108a is also inconsistent with the X-ray behaviour of both of these events which display emission over tens of days at luminosities incompatible with the upper limits we derive above. At this time cannot

rule out similar behaviour to that seen in another LFBOT CSS161010 (Coppejans et al. 2020; Gutiérrez et al. 2024a) which displayed lower luminosity X-ray emission at a ~ 100 days post-outburst. Similarly, our current radio limits for SN 2025kg are compatible with the behaviour seen in the LFBOT sample which are still rising at a comparable time.

To conclude, SN 2025kg is inconsistent with many properties of LFBOTs at optical and X-ray wavelengths and it is unlikely that the same progenitor system is responsible for producing both classes of transient.

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